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Abstract

The Apennines-Sicilian-Maghrebian fold-and-thrust belt originated from the subduction of the Alpine Tethys and the later collision of drifted continental blocks against the African and Apulian paleomargins. From North to South, the Sicilian Fold-and-Thrust Belt (SFTB) is divided in four main tectono-stratigraphic domains: (1) the Calabro-Peloritani terrane, drifted from the European margin, (2) the remnants of the Alpine Tethys accretionary Wedge (ATW) related to the subduction of the Tethys, (3) the folded and thrusted platform (Panormide) and deep-water (Imerese-Sicanian) series of the offscrapped African margin, and (4) the African foreland (Hyblean). Unfortunately, apart from central Sicily (Catalano et al., 2013a), scarce quality seismic lines (Bianchi et al., 1987; Bello et al., 2000) and outcrops of key tectono-stratigraphic units make the structure and dynamic evolution of the central-eastern part of the SFTB controversial.

First, this study outlines through a review of the tectono-stratigraphic evolution of the central-eastern sector of the Sicilian orogen, the major remaining issues concerning: (1) the occurrence of inferred Alpine Tethys units far from the region where the remnants of the

ATW outcrop (Nebrodi Mountains); both, in a forearc position above the Peloritani block to the North and in an active foreland context along the present day southern front of the belt; and (2) the diverging tectonic styles, from stacked large-scale tectonic nappes to foreland imbricated thrust systems rooted into a main basal décollement.

Secondly, new constraints are given using analogue modeling to test mechanically the hypothesized structural and tectono-stratigraphic evolution of the SFTB. The experiment simulates the orogenic evolution of the SFTB at crustal-scale, from the Oligocene Tethys subduction, to the Middle Miocene-Late Pliocene continental collision between the European and African paleomargins. The tectono-stratigraphic synthesis is used to model the first-order mechanical stratigraphy of the sedimentary units involved in the Sicilian belt, as well as the imprint of the African margin structural inheritance.

The experiments succeed in reproducing the general structure and tectono-stratigraphic evolution of the SFTB. In particular, the models support field observations hypothesing a gravity-driven origin of the inferred Alpine Tethys units intercalated within the forearc and foreland syntectonic sedimentation. Moreover, the model testifies of the main tectonic steps that led to the SFTB building. First, a low-tapered accretionary wedge was accreted above the Alpine Tethys oceanic crust from the Oligocene to the Early Miocene. The following underthrusting of the stretched African continental margin and its frontal Panormide platform shortened and thickened the accretionary wedge. This phase provided favorable conditions for significant pulses of reworked Alpine Tethys units that intercalated within the forearc and foredeep successions. During the Middle-Miocene, the décollement of the African Meso-Cenozoic cover (Panormide platform and Imerese-Sicanian deep-water basin) enhanced a deep-seated deformation phase, along with duplexing of the Panormide platform beneath the Alpine Tethys wedge leading to its emersion. Since the Late Messinian, activation of basement faults led to a generalized emersion of the orogenic units through large-wavelength fold culminations accompanied by syn-tectonic deposition at their southern limbs (Barreca, 2015; Gasparo Morticelli et al., 2017). Concurrently the prism front was partly indented to the southeast by the thick and locally already emerged Hyblean platform.

I - Introduction

Since at least the late Cretaceous, the geodynamics of the Mediterranean Basin has been controlled by the Africa/Eurasia plates convergence and by the migration of long and narrow highly mobile orogens in response to slab roll-back and trench retreat mechanisms (e.g., Malinverno and Ryan, 1986; Doglioni et al., 1997, Doglioni et al., 2007). These latter highly dynamic processes induced local convergence rate one order faster than the global plate tectonics as testified, by the ~ 10 cm/y opening of the Tyrrhenian back-arc basin and associated southeastward migration of the Calabrian Arc over the past 7-9 My (e.g., Rosenbaum and Lister 2004, Royden and Faccenna, 2018). In this geologic context, the Sicilian Fold and Thrust Belt (SFTB, Figure 1 and Figure 2) is considered as a segment of the Apennines-Maghrebian Chain which separates the Mesozoic Eastern Mediterranean basin (Ionian Sea) from the Western Mediterranean Cenozoic back-arc basins: the Liguro-Provençal and the Tyrrhenian basins (e.g. Dewey et al., 1989).

From NW to SE, the southern Apennines-Sicilian Belt is divided into four main tectono-stratigraphic domains (Figure 2 and Figure 3): (1) the Calabro-Peloritani block, derived from the European margin; (2) the Alpine Tethys units (Sicilides and Ligurides), overthrusted above (3) the platform (Panormide and Campania-Lucania) and deep-water (Imerese-Sicanian and Lagonegro-Molise) successions of the down-going African and

Adriatic margins, (4) whose foreland units are outcropping in southeastern Sicily (Hyblean) and in the Apennines (Apulia).

A wide variety of geodynamic processes have been proposed to account for the strong arched shape of the Apennines-Sicilian Belt (Figure 1 and Figure 3e), such as the forced eastward extrusion induced by the African plate indentation (Tapponnier, 1977; Mantovani al., 1993), lithospheric buckling (Johnston and Mazzoli, 2009), or differential slab retreat velocities from the Ionian oceanic corridor to adjacent continental African and Adriatic promontories (Malinverno and Ryan 1986; Royden et al., 1987). Analogue models have shown that these processes are not exclusive and the geodynamics of the Tyrrhenian system could have been controlled by both; the northward indentation of the African plate and, the fast eastward trench retreat (e.g., Faccenna et al., 1996).

In addition to the driving force controversy of the Apennines-Sicilian system, paleogeographic considerations are crucial for a complete understanding of the orogenic evolution. Indeed, the slab-pull force driving the slab rollback mechanism and associated back-arc extension requires a significant negative buoyancy of the plunging slab commonly procured by “old” and dense Mesozoic oceanic lithospheres (e.g., Forsyth and Uyeda, 1975). Other mechanism are expected to control the subduction dynamic, such as the upper plate absolute motion relative to the anchored slab as well as the large-scale or local mantle flow surrounding the slabs (e.g., Conrad and Lithgow-Bertelloni, 2002; Lallemand et al., 2005; Heuret and Lallemand, 2005; Doglioni et al., 2007; Becker and Faccenna, 2011; Carminati and Doglioni, 2012). Nevertheless, the arrival of continental lithosphere in the subduction zone necessarily has consequences on the wedge mechanics, and the evolution of the retreating slab can follow different scenarios such as delamination, continental subduction or break-off (e.g., Magni et al., 2013 and references therein). Because only the oceanic lithosphere can durably sustain the subduction system, it is of major interest in the confined Mediterranean system.

Unfortunately the paleogeography of the Western Mediterranean system is non-consensual, particularly considering the nature and width of the continent/ocean transition between the eastern Alpine and the western Ionian Tethys oceanic domains (Carminati et al., 2012 and references therein). On one side, the contemporaneous occurrences of similar Late Jurassic-Cretaceous dinosaurs in Apulia and Africa (Rosenbaum et al., 2004; Zarcone et al., 2010) and the relatively coherent paleomagnetic motion paths of Africa and Adria since the Jurassic suggest a possible continental connection between these two domains (Stampfli and Borel, 2002, 2004; Stampfli and Hochard, 2009; Frizon de Lamotte et al., 2011; Van Hinsbergen et al., 2020). On the other side, the presence of a narrow oceanic domain (400-600 km wide) since the Late Jurassic or Cretaceous cannot be ruled out by these previous arguments and is generally assumed in most of paleogeographic reconstructions on the basis of tectono-stratigraphic compilations, the analysis of seismic profiles together with the interpretation of tomographic sections (Dercourt et al., 1986; Catalano et al., 2001; Faccenna et al., 2001, 2004, 2014; Finetti, 2005; Cifelli et al., 2007; Handy et al., 2010). Within this framework, the geodynamic evolution of Central Mediterranean was constrained by a complex three dimensional setting involving purely oceanic to stretched continental lithospheres (e.g., Chiarabba et al., 2008; Carminati and Doglioni, 2012; Mantonavi et al., 2014) that led to the formation of the Apennines-Sicilian Belt (Figure 3).

The SFTB appears as a central piece of the Mediterranean orogenic subduction systems and its understanding is essential to constrain paleogeographic models of the Mediterranean and, more generally, the dynamics and mechanics of subduction related orogens. Many studies focused on the stratigraphy of Sicilian units (e.g., Patacca et al., 1979; Avellone et al., 2010; Guerrera et al., 2012; Pinter et al., 2016; Basilone, 2009, 2018), local (e.g., Oldow et al., 1990; Catalano et al., 1995, 1996; Zarcone et al., 2010; Vitale et al., 2018), regional paleogeographic settings (e.g., Dewey et al., 1989; Stampfli and Borel, 2002; Carminati et al., 2012; Handy et al., 2010; Frizon de Lamotte et al., 2011; Van Hinsbergen et al., 2020), internal structure of the SFTB (e.g., Roure et al., 1990; Avellone et al., 2010; Guarnieri et al., 2002; Catalano et al., 1995, 1996 and 2013a) and tectono-stratigraphic reconstructions (e.g., Roure et al., 1990; Corrado et al., 2009; Guerrera et al., 2012; Napoli et al., 2012; Gugliotta et al., 2011, 2014; Butler et al., 2019; Basilone et al., 2016; Basilone, 2020). However, only a few studies were dedicated to the Sicilian orogen dynamics and, in particular, to constrain the small and large scale deformation mechanisms controlling its structural evolution (e.g., Balestra et al., 2019; Ben-Avraham et al., 1995; Barreca and Monaco, 2013).

In this study, we present a general synthesis of the paleogeography (Figure 3) and tectono-stratigraphy (Figure 4 and Appendix A) of the central-eastern SFTB to set up a conceptual reconstruction based on previous works and field observations. This “a priori” model is then tested using 2D analogue experiments to evaluate its mechanical validity. To that end, we critically reviewed an extensive literature concerning the tectono-sedimentary structure of the SFTB and constrained its mechanical stratigraphy by means of complementary field observations. The latter were performed along a regional geo-transect documenting the SFTB evolution (yellow line in the Figure 3e). The modelisation aims to study the internal deformation within major tectonic units forming the backbone of the SFTB, and to evaluate the paleogeography of the African margin prior to the collision. The initial state and boundary conditions applied during the analogue experiment are able to reproduce the dynamics of specific accretionary wedges such as the SFTB. Indeed, following previous works on Western Alps (Bonnet et al., 2007) Taiwan (Malavieille and Trullenque, 2009) mountain belts, we performed 2D analogue models including syntectonic erosion and sedimentation, structural and stratigraphic regional inheritance as well as synkinematic flexure. The outcomes of the simulation are then challenged to the literature and key field observations to afford new constraints and hypothesis on the SFTB mechanics, kinematics and related surface processes.

II - Tectono-stratigraphy of central-eastern Sicily: overview and hypotheses

To synthetize the tectono-stratigraphic evolution of the Sicilian Fold and Thrust Belt (SFTB), it is necessary to take into account all information concerning, lithostratigraphy, paleogeography, and tectonics of central-eastern Sicily. Therefore, in this section we: (1) summarize the lithostratigraphy of Sicilian units and the corresponding Mediterranean geodynamics, (2) outline the structural and tectonic constraints, (3) discuss the origin of inferred Alpine Tethys units within the forearc and foreland basins with supporting field observations and (4) propose a conceptual tectono-stratigraphic model that will serve as a reference to design analogue models, determine scaling and boundary conditions.

II.1 - Lithostratigraphy and paleoenvironment of Sicilian units

II.1.1 - *Paleozoic*

Aside from the Paleozoic metamorphic rocks from the European margin outcropping in the Peloritani mountains (Figure 2), the oldest lithologies found in Sicily contain Permian microfauna (Lercara Fm.). These shallow to deep-water deposits sign the western termination of the Alpine Tethys oceanic domain in the post-collisional tectonic setting of the Variscan orogeny and associated widespread Permian Pangean extension (Catalano et al., 1991; Stampfli and Borel, 2002). These clast-bearing deposits, outcropping in central-western Sicily, are also believed to have formed in an intra-continental rift, partly supplied by the erosion of the adjacent Permian carbonates during the Middle-Triassic (Catalano and D'Argenio, 1978; Basilone et al., 2016). Indeed, paleogeographic studies have shown that the Permian lithologies in Sicily were reworked and resedimented during the Trias (Cirilli et al., 1990; Carcione et al., 2004), possibly following the emersion and erosion of Permian platforms in the western branch of the Neotethys.

II.1.2 - ***Mesozoic***

Following the Late Paleozoic northeastern Gondwana break-up, the rifting remained active during the early Mesozoic. The last stages of the break-up mainly appeared during the Jurassic, starting in the Central Atlantic and propagating eastward to form the Alpine Tethys (e.g., Favre and Stampfli, 1992). Then, in the Early Cretaceous, further extension of the Alpine and Ionian Tethys occurred, as testified by paleomagnetic reconstructions (Handy et al., 2010; Van Hinsbergen et al., 2020 and references therein) and fault activity along the Malta Escarpment (Catalano et al., 2001). However, the opening process at the origin of the Ionian basin is still debated, particularly in terms of kinematics and role of the Malta Escarpment at that time, evolving from passive to transform margin (Catalano et al., 2001; Frizon de Lamotte et al., 2011; Gallais et al., 2011, Dellong et al., 2018). As a consequence, the connection between the Alpine and Ionian domains to the East is still non-consensual (Figure 3a).

Setting aside the Permian-Lower Triassic formations, which are poorly or not outcropping in Sicily, the lowermost formation characterizing the base of the Meso-Cenozoic cover of the African margin is represented by the Triassic flysch-like marly limestones of the Mufara Fm. (Basilone, 2009, 2018). Above it, a major Upper Triassic carbonate sequence deposited on the northwestward (Panormide, column C from Figure 4 and Appendix A) and southeastward (Trapanese-Saccense and Hyblea, column F and G from Figure 4 and Appendix A) platforms of the African paleomargin (Basilone, 2009, 2018), whereas deep-water carbonates and siliceous deposits sedimented in intermediate basins (Imerese and Sicanian, column D and E from Figure 4 and Appendix A). The Imerese and Sicanian domains are believed to belong to the Ionian Tethydes (the so-called "Ionides", Finetti, (2005), including also the Lagonegrese units of southern Apennines) in a stretched continental to oceanic crust setting (OCT) deriving from the Late Paleozoic to early Mesozoic eastern Gondwana break-up.

The lithology and paleoenvironments of the Sicilian Jurassic and Cretaceous series reflect the African margin structuration inherited from the Triassic rifting (Catalano and D'Argenio, 1978) and partly reactivated during Mesozoic events. Inherited structural highs (Panormide, Trapanese-Saccense and Hyblean platforms) show relatively shallow-water facies with carbonate platform deposits accompanied, in the Trapanese-Saccense and Hyblean realm, by some deeper pelagic sequences locally containing radiolarians (Basilone, 2009, 2018). These drowning episodes, in particular during the Toarcian event, likely appear together with major eustatic rise (Hermoso et al., 2013), accompanied by abrupt tectonic and long-term thermal (Yellin-Dror et al., 1997) subsidence phases following the extension of the continental African margin (Sulli and Interbartolo, 2016).

In the basins, deep-water deposits are testified by the presence of radiolarites and pelagic sediments (Basilone et al., 2016) with sometimes, in the Imerese domain, resedimented shallow-water carbonates originated from the surrounding and possibly emerged platforms (Basilone, 2009, 2018 and references therein). However, it can be noticed that Mesozoic radiolarites deposited all around the Tethys. They are usually associated to deep-water environments below the CCD, but also explainable by high sea water silica concentrations coming from oceanic spreading centers active during this period (Jenkyns and Winterer, 1982). Thus the deep paleobathymetry inferred from these units must be handled carefully.

Later in the Jurassic-Cretaceous, the paleobathymetry of the Sicanian domain catches up the Trapanese-Hyblean level where common pelagic carbonates are sedimented.

The oldest sediments from the Alpine Tethys (Figure 4, columns B and Appendix A) outcropping in the SFTB are Cretaceous in age and are represented by deep-water flyschs and scaly clays showing locally evidences of strong internal deformation ("argille scagliose", Ogniben, 1953). Moreover, Mesozoic sedimentary sequences are also found in the Peloritani block where they constitute the remnants of the European margin cover (Bouillin et al., 1992).

II.1.3 - ***Paleogene***

Although poorly understood, some rotation and independent movement of the Adria plate might have occurred during the Paleocene-Eocene (Handy et al., 2010; Le Breton et al., 2017) and could possibly be related to a drowning episode affecting the African margin (Gumati et al., 1985; Frizon de Lamotte et al., 2011). Indeed, prior to its northward collision ~ 35 Ma ago, Adria's counter-clockwise rotation is thought to have been accompanied by renewed spreading in the Ionian Tethys (Le Breton et al., 2017) as well as a quasi-continuous extension within the Pelagian realm from the Sirt basin to the Sicily Channel (Gumati et al., 1985; Capitanio et al., 2009; Frizon de Lamotte et al., 2011). Contemporaneously, the

Middle-Eocene subduction polarity inversion replaced the ending SE plunging western Alpine Tethys by a NW plunging eastern Alpine Tethys (Ligurian ocean) below the Alboran-Kabylies-Peloritan-Calabria (AlKaPeCa; Bouillin et al., 1986) and Balearic-Sardinia-Corsica blocks (Molli, 2008, Molli and and Malavieille, 2011, 2012). This new-coming subduction signed the onset of the Apennines-Sicilian-Maghrebide subduction system that is still partly active today. Then, the Oligocene widespread crustal extension affecting the European margin gradually dismembered the Pyrénées-Provence belt, the Alpine foreland (Corso-Sarde blocks) and the Alpine-Betic chain signing the onset of back-arc basins that now constitute Western Mediterranean (e.g., Jolivet et al., 2018).

From Late Cretaceous to Eocene, most of the African margin was drowned under a few hundred meters of water (Dewever et al., 2010; Vitale et al., 2018) while locally, emerged highs underwent subaerial erosion (Roure et al., 2012) inducing deposition of calcareous megabreccias (Di Stefano et al., 1996). These locally subsinding and uplifting zones are possibly related to vertical tectonic activity in response to the Africa-Eurasia convergence (Yellin-Dror et al., 1997; Dewever et al., 2010; Nigro and Renda, 2002; Vitale et al., 2018).

Throughout that period, the widespread pelagic and hemipelagic sedimentation of marly limestones (Amerillo Fm. and Caltavuturo Fm.) attest of a slow subsidence along the African margin (Basilone, 2018 and references therein). On the Panormide promontory, shallow-water reef-building carbonates deposited mostly from the Upper Triassic to the Lower Cretaceous, then followed up in the Eocene by a quasi-open shelf marly sedimentation (i.e., the Upper Eocene Gratteri Fm.). Later, during the Oligocene, the sedimentation continued with pelagic carbonates depositing above the Panormide and Trapanese-Hyblean promontory together with marly sequences in the deeper Imerese and Sicanian realm (Finetti, 2005 and references therein).

In the Alpine Tethys realm, deep-water sedimentation dominated while evidences of terrigenous sedimentation on the active European margin are testified by calcareous breccias preserved in the Calabro-Peloritani units (Lentini et al., 1995).

Later, during the Oligocene, deep-water varicolored clays (the so-called "Variegated" clays or also "Argile Scagliose", Ogniben, 1953) were deposited in the Alpine Tethys realm (Belayouni et al., 2006; Guerrera et al., 2005; Finetti, 2005), with locally whitish marly calcareous and calcarenitic turbidites (Polizzi Fm.), both characterizing the "Sicilide complex".

First occurrence of a major turbiditic sequence along the southern Alpine Tethys margin, the so-called "Numidian Flysch" (Ogniben, 1960), recognized from the Gibraltar Arc to southern Apennines (Caire and Mattauer, 1960) dates back to the Upper Oligocene (Johansson et al., 1998 and citations therein). Although non-consensual and discussed further, the innermost "Numidian Flysch" probably started to deposit between the accretionary wedge and the African margin edge in an unconfined deep-sea environment (e.g., Guerrera et al., 2012), such as in the Maghrebian system to the west (Frizon de Lamotte et al., 2000). During Upper Oligocene, these turbidites are mostly composed of brown-clays with quartzarenite intercalations (Nicosia and Mt. Salici subunits, also named "far travelled" Numidian Flysch) while volcaniclastic sequences of the Troina subunit (Tusa tuffites Fm.) were deposited in the internal domain of the Alpine Tethys (Bianchi et al., 1987). These volcaniclastic sediments might sign the major volcanic activity occuring in Sardinia at that time, and likely associated to the onset of slab rollback and back-arc extension (Beccaluva et al., 2011; Carminati et al., 2012).

Stacked against the Peloritani block, the Oligocene to Lower Miocene conglomerates and flysch-type trench-fill deposits (Piedimonte Fm.) constitute the early accretionary prism (Figure 3a) developing at the front of the migrating Corso-Sardinian block (Lentini and

Carbone, 2014; Finetti, 2005; Belayouni et al., 2006). Flyschs and basal conglomerates (Conglomerato Rosso Fm.), deposited above the Calabro-Peloritani block, also testify of the terrigenous supply from the European counterpart (Finetti, 2005). Upward, the sequence called Capo d'Orlando Fm. then turns from thrust-top molasse to flysch-type sediments (Ogniben, 1960; Lentini and Carbone, 2014; Belayouni et al., 2006), whose detritical source comes from the erosion of the emerged parts of the Calabro-Peloritani block (Cavazza, 1989; Thomson, 1994). The significant forearc infill by the Capo d'Orlando turbidites initiated during the early deformation of the Peloritani-Calabria block (still attached to the Corso-Sarde block at that time), as evidenced by the Late Oligocene Alpine metamorphic overprint of the Peloritani crystalline basement (Atzori et al., 1994) and its late orogenic exhumation (Thomson, 1994).

II.1.4 - *Early to Middle Miocene (Aquitanian to Langhian)*

The Early Miocene geodynamic setting of central Mediterranean is dominated by (Figure 3a): 1) the 60° counter-clockwise rotation of the Corso-Sardinian block (Montigny et al., 1981; Dewey et al., 1989), 2) the collision of the Kabilyan blocks with the African margin, and 3), the incipient separation of the Peloritani-Calabria block from the southeastward traveling Corso-Sardinian block (e.g., Rosenbaum et al., 2002).

The Lower Miocene sedimentation is dominated by the previously introduced Numidian Flyschs (Ogniben, 1960). The major quartz source of the Early Miocene quartzarenite-rich Numidian Flysch has long been debated, from orogenic to cratons domains in Africa (Finetti, 2005 and citations therein). Recent works on detritical zircon ages from Numidian sequences rather constrain that the main sources are the African cratons (Thomas et al., 2010; Guerrera et al., 2012) and that this terrigenous supply, extending all along the southern Alpine Tethys, might be associated to long-wavelength forebulging of the African margin during the closure of the Tethys domain (Guerrera et al., 2012). Another emerged controversy concern their depositional environment, from partly confined by active tectonic structures (Pinter et al., 2016, 2018; Butler et al., 2019) to unconfined depocenters (e.g. Bianchi et al., 1987; Guerrera et al., 2012). The unconfined model (Guerrera et al. (2012) suggests that the "far travelled" Numidian Flyschs filled the southern Alpine Tethys realm up to the base of the African margin (Panormide-Tethys transition), while forearc and intra-arc flyschs (Tusa tuffites Fm. and Troina sandstones) constituting the upper "Sicilide complex" were sedimented in the growing Alpine Tethys accretionary Wedge (ATW). Above the gently flexed African margin, Numidian Flyschs were covering the top of the Panormide and Imerese succession (Geraci Siculo member; Basilone, 2011) and were progressively grading up into Burdigalian-Langhian pelagic marls (Castelbuono and Tavernola marls of the Panormide and Imerese successions). On the other hand, the confined scenario of Pinter et al. (2016) propose; the megasequence of Numidian turbidites in the Madonie and Nebrodi mountains could have accumulated mostly in the Burdigalian, during a short event (1-3 Ma); and inside elongated basins controlled by the frontal active thrusts of the ATW rather than by the Mesozoic margin structural inheritance.

Aside from the controversy, in the inner part of the growing Alpine Tethys accretionary wedge, thrust-top terrigenous sediments are also deposited from that period and hold a Calabro-Peloritani source different from the coeval Numidian Flysch (Reitano Fm.; de Capoa et al., 2004; Puglisi, 2014). Southward and closer to the African continent, the corresponding Numidian sequences are represented by Burdigalian-Langhian marls, glauconitic calcarenites and pelagic ramp carbonates covering the Sicanian-Trapanese-Hyblean realm.

Finally, above the Peloritani block (Figure 2), the sedimentation of the aforementioned Capo d'Orlando forearc sequence, deposited in a forearc setting at the rear of the Alpine Tethys Wedge (ATW), was suddenly interrupted by an Upper Burdigalian intercalation of chaotic varicolored clays (column A from Figure 4 and Appendix A). These varicolored clays, similar to that of the Sicilide complex, and so-called "Antisicilide Fm." by Ogniben, (1960), were then quickly covered by the return of the forearc sedimentation (Floresta calcarenites, Giunta and Nigro, 1999) from late Burdigalian/Langhian (Figure 4, column A). Because the Antisicilide Fm. was dated to Late Cretaceous-Eocene, some authors proposed that this unit has been tectonically backthrusted above the Peloritani forearc basin (Corrado et al., 2009). This hypothesis remains highly speculative and will be discussed in details further since the Antisicilide depositional event could also reveal gravitational instabilities at the rear of the wedge.

II.1.5 - ***Middle to Upper Miocene (Serravalian to Messinian)***

The Alpine Tethys accretionary Wedge (ATW) continued propagating southeastward reaching the first highs of the stretched African continental margin (Figure 3b and 3c). The Meso-Cenozoic cover of the margin then started to accrete and build the orogenic wedge, although part of it was progressively underthrusted below the ATW (Wezel, 1974; Giunta, 1985). This period was also characterized by large vertical-axis clockwise rotations of the thrust system in response to the convergence obliquity. Up to 70° regional rotations of Upper Triassic-Middle Miocene successions are recorded by paleomagnetic measurements (Channell et al., 1990; Oldow et al., 1990; Speranza et al., 2003, 2018) and structural analysis (Monaco and De Guidi, 2006; Avellone et al., 2010; Barreca and Monaco, 2013).

Meanwhile, pelagic marls and marly clays deposited in the adjacent foredeep (San Cipirello marls and then Licata Fm.) while wedge-top depozones (Figure 4, column H and Appendix A) and proximal foredeep continued to be filled during the Serravallian-Lower Messinian by clastic sediments, including metamorphic cobblestones (Castellana Sicula Fm., and then Terravecchia Fm.; Ruggieri and Torre, 1982; Abate et al., 1999; Finetti, 2005; Gugliotta, 2011; Catalano et al., 2011; Barreca, 2015). Consequently, the main source of these later deposits is likely related to the erosion of emerged parts of the orogenic prism and the Peloritani-Calabria block.

During the Messinian Salinity Crisis, the syntectonic sedimentation proceeded with evaporitic sequences (gypsum and carbonates) in tectonically-controlled restricted depozones along the northernmost margin of the Caltanissetta Basin (Roveri et al., 2008; Butler et al., 2015, Gasparo Morticelli et al., 2017). Messinian evaporites are also found in the northern side of the Peloritani, above the San Pier Niceto terrigenous formation (Finetti, 2005). In response to sea level drop (> 1000 m), most of the orogenic prism temporarily emerged inducing a major erosional pulse comparable to documented Messinian detritic deposits along the Western Mediterranean margins; Gulf of Lion (Bache et al., 2009), Ligurian (Obone-Zue-Obame et al., 2011), Sardinian (Sage et al., 2005) and Valencia (Maillard et al., 2006) slopes as well as in Eastern Mediterranean offshore of Cyprus (Gorini et al., 2015). The associated erosion products supplied the Ionian basin to the southeast and the Tyrrhenian basin to the northwest (Figure 3d).

II.1.6 - ***Pliocene-Pleistocene***

The Tyrrhenian back-arc spreading (Figure 1 and Figure 3d) mostly occurs during the Plio-Pleistocene timespan (Faccenna et al., 2004) and possibly leads to vertical motion of northern Sicily related to mantle flow surrounding the southeastward retreating Ionian slab (Faccenna et al., 2011). In addition, during the Pleistocene, the subduction hinge retreat relative to the upper plate progressively slowed down in Sicily (Carminati and Doglioni, 2012; Doglioni et al., 2012). Contemporarily, a contractional belt initiated all along the southern Tyrrhenian basin, from the Aeolian Islands to the Sardinia strait (Figure 1), characterized by inversion tectonics due to the ongoing convergence between Africa and Eurasia (Pepe et al., 2004).

The tectonic shaping of the “Gela nappe”, mostly occured during the Plio-Quaternary in response to the identation of the wedge by the thick Sciacca and Hyblean platforms (Lickorish et al., 1999). It resulted in the formation of a second-order orogenic arc in the Sicilian-Apennine system (Doglioni, 1991). Since Middle-Late Pleistocene, the emersion of the northernmost margin of Sicily was probably driven by slab detachment and associated lithospheric elastic rebound (Gvirtzman and Nur, 1999; Barreca et al., 2016), an ongoing process testified by Late Quaternary strong uplift of NE Sicily (Ferranti et al., 2006).

Along with the sea-level rise that followed the Messinian Salinity Crisis, the inherited and ongoing piggyback setting was associated to Lower Pliocene pelagic marls (Trubi Fm.) unconformably overlying the aforementioned deposits (Butler et al., 1992). The syntectonic sedimentation proceeded upward with Upper Pliocene-Pleistocene terrigenous and carbonate-clastic sequences (Catalano et al., 1993; 1998; Vitale, 1990, 1998; Grasso et al., 1995; Gasparo Morticelli et al., 2015) filling major tectonic depressions such as the Caltanissetta basin in central Sicily (Enna marls, Capodarso calcarenites and Geracello marls and overling sands), the Castelvetrano basin to the west (Belice marly-arenaceous Fm.), and the Gela foredeep to the east (marls of the Ponte Dirillo Fm. and Gela turbidites; Ghielmi, 2012). This complex tectono-sedimentary setting is coeval to the southeastward propagation of the SFTB front (Figure 3e), also referred as the “Gela nappe”, and eustatic fluctuations (e.g., Catalano et al., 1996; Grasso et al, 1995; Gasparo Morticelli et al., 2015).

Continental and marine Quaternary deposits outcrop locally, mainly along the Sicilian coast, but that period is mostly characterized by unconformity erosional surfaces related to the recent emersion of Sicily (Ferranti et al., 2006; Agate et al., 2017).

II.2 – Main established tectonic constraints and remaining issues

According to the previously described Sicilian lithostratigraphy, the general structure of the SFTB can be divided into four domains from: (1) a relict of the European margin mainly composed of metamorphic crystalline basement units and its Mesozoic sedimentary cover (column A, Figure 4), (2) Allochthonous “oceanic” units constituting the remnants of the Alpine Tethys accretionary wedge (columns B, Figure 4), (3) stacked Meso-Cenozoic platform and basinal units of the northern African margin (columns C, D, E and F, Figure 4), and (4) the thick African continental foreland (column G, Figure 4) separated to the front of the SFTB by the modern foredeep extending onshore from Catania to Gela. Excluding the Variscan signature of the European remnants, the deformation events that progressively built the Sicilian wedge show a quasi-continuous tectonic history starting from the Paleogene Alpine orogeny as evidenced by the low-grade alpine metamorphism affecting the Peloritani-Calabria block (Atzori et al., 1994). However, the building of the SFTB only became effective since the Middle-Late Miocene (Figure 4) with the onset of the subduction of the stretched African continental margin and associated oceanic realm (Roure et al., 1990). Despite questioning about the recent activity of the SFTB (Monaco et al., 1996; Lavecchia et al., 2007; Barreca et al., 2014), there is a general agreement to say that crustal shortening drastically decreased since the Pleistocene, in accordance with the low convergence rates (< 5 mm/yr) measured geodetically (e.g. Palano et al., 2012; Mastrolembo Ventura et al., 2014).

The early deformations associated to the migrating Peloritani-Calabria block and associated frontal Alpine Tethys accretionary Wedge (ATW) are only outcropping in northeastern Sicily and Calabria (Figure 1 and Figure 2). That is why we mainly focused on central-eastern Sicily where most of the tectonic units are still preserved along a <100 km N-S transect (Figure 2 and Figure 3e), from the European remnant (Peloritan) to the African foreland (Hyblean). Effectively, due to the previous merging of the Trapanese and Hyblean platforms to the west, only the thick Trapanese sequence is lacking in central-eastern Sicily, (Nigro and Renda 1999; Oldow et al., 1990).

II.1.1 - ***Continent-ocean transition***

Some opened questions arise in Sicily when looking at the key processes related to subduction and collision systems. Where are the remnants of the Alpine Tethys realm? When did the oceanic to continental subduction really started? What was the nature of the Alpine Tethys and Ionian basin connection? What happened to the southeast retreating slab? Although these questions need significant additional work to be properly answered, paleogeographic scenarios are selected and discussed with regard to the further modelisation outcomes.

Ophiolites are undeniable proofs of closed oceanic realm and mark the suture zone between distinct continental lithospheres involved in a collision process. Nevertheless, unlike in the Apennines, the negligible or complete lack of ophiolitic bodies in Sicily as well as in the Tell-Rif orogenic system (Durand-Delga et al., 2000; Roure et al., 2012; Michard et al., 2014; Leprêtre et al., 2018) raises issues concerning the width and nature of the transition zone between the African margin and the Alpine Tethys domain (Figure 3a). Indeed, the lack of ophiolite is not necessary the sign of a poorly oceanized Tethys but could reflect a limited accretion of oceanic crust material within the prism. It is the case for accretionary wedges experiencing tectonic erosion and, then, significant material subduction (Shreve and Cloos, 1986; Gutscher et al., 1998; Beaumont et al., 1999), and also wedges built from oceanic floor covered by a thick sedimentation. This is a probable setting for the Apennines-Sicilian Belt as suggested by the sediment-enriched mantle source detected in the subduction-related Miocene volcanism from Sardinia (Barberi et al., 1974; Avanzinelli et al., 2009). On the other hand, the occurrence of scarce Tethysian E-MORB (enriched MORB) in the Sicilian and Tell-Rif belt, characteristic of rift setting, and the complete lack of N-MORB, typical of oceanized domains, is in favor of a poorly oceanized southern "slow spreading" Alpine Tethys (Durand-Delga et al., 2000). It is therefore probable that the northern African margin was mostly constituted by a wide Ocean-Continent Transition (OCT) inherited from a transform tectonic setting linking the Atlantic to the Tethys during the Jurassic (Durand-Delga et al., 2000).

The same problematic arises concerning the nature of the substratum between the western Alpine and eastern Ionian Tethys (Dercourt et al., 1986; Catalano et al., 2001; Faccenna et al., 2001; Stampfli and Borel, 2002, 2004; Rosenbaum et al., 2004; Finetti, 2005; Cifelli et al., 2007; Stampfli and Hochard, 2009; Handy et al., 2010; Frizon de Lamotte et al, 2011; Carminati et al., 2012; Vitale et al., 2018, 2019), the latter being currently consumed by the SE-vergent subduction beneath Calabria (Figure 1 and Figure 3e). It has been proposed that a continental lithosphere with a relatively thin crust (< 15 km) can subduct under high slab pull force conditions (Cloos, 1993; Chemenda et al., 1995) and recent models confirmed that this process is mechanically possible over a few hundreds of kilometers (Edwards et al., 2015). Hence, whereas the oceanic continuity between the western and eastern Tethys is still debated, we assume a continuous retreating slab from the Alpine Tethys to the contemporaneous Ionian subduction (Figure 3), without subduction jump or terrane accretion, and provided during the Neogene the main driving tectonic forces at the origin of the SFTB.

II.2.2 ***Tectonic style and accommodation of crustal shortening***

Wedge mechanics and deformation partitioning in the SFTB is non-consensual as testified by the radically opposed models that emerged, most of them being based on surficial geology, reflection seismic data and boreholes (e.g., Bianchi et al., 1987; Roure et al., 1990; Lentini et al., 1990; Bello et al., 2000; Catalano et al., 2000; Accaino et al., 2011; Catalano et al., 2013a; Gasparo Morticelli et al., 2015). On one side, seismic profiles (Figure 5a and 5e), are interpreted with large-scale nappes and duplexing implying very large crustal shortening, up to ~ 300 km (e.g., Bello et al., 2000; Catalano et al., 2013a; Gasparo Morticelli et al., 2015). On the other side (Figure 5b), recent analysis of synkinematic sedimentation suggests much smaller crustal shortening (< 100 km) associated to ramp-dominated structures coupled to an initial long distance (~ 200 km) displacement of the whole ATW along a unique basal detachment (Butler and Lickorish, 1997; Butler et al., 2019). To that extent, large displacements are expected in the first model between the main lithostratigraphic units (Sicilide, Panormide, Imerese, Sicanian, Trapanese and Hyblean), and much lower ones in the latter tectonic reconstruction (Butler et al., 2019).

As previously noticed, moderate differential rotation between coeval tectono-stratigraphic units within the wedge, and major decreasing rotation through time, evidenced by paleomagnetic data (Cifelli et al., 2007; Speranza et al., 2018), are not consistent with large displacements between long thrust sheets (Butler et al., 2019).

The radically different tectono-stratigraphic model proposed by Butler et al. (2019) rather favors minor doubling of Numidian Flysch units by tectonic contact (Figure 5b), an hypothesis that might be supported by the recent reassessment of the Numidian turbidites as syntectonic massive deposits by Pinter et al., (2016, 2018). In the Mt. Judica area (see location in Figure 5), these authors argue for continuous synkinematic sedimentation above the deep-water pre-kinematic substrate since the Early Miocene, with deposits mostly ponded on top of the thrust wedge and a very limited foredeep infill. While the authors claim for > 2000 m thick synkinematic Numidian turbidites associated to the Judica thrust stack located at the wedge front, no significant Early-Middle Miocene turbidites are found ahead. Unless being completely underthrusted beneath the wedge, the lack of Miocene turbidites south of the SFTB front (Figure 5b) is however not in favor of such predominant synkinematics sedimentation. Their model also suggests in northern Sicily (Madonie and Nebrodi Mountains), a fold and thrust system involving the Panormide unit since the Aquitanian (Pinter et al., 2018) while structural studies have shown that the deformation rather started in the Middle-Upper Miocene (Roure et al., 1990; Napoli et al., 2012; Gugliotta and Gasparo Morticelli, 2012; Barreca and Monaco, 2013; Van Hinsbergen et al., 2020 and references therein). More likely, the lower Numidian deposits (Late Oligocene-Early Miocene) were not deposited over the wedge but in the trench/foredeep basins. In the frontal Mt. Judica area, only the late Serravalian sequences of the glauconitic Numidian equivalent were sedimented in piggyback depocenters controlled by the stacking of the deep-water units in the vicinity of the Hyblean Platform.

According to recent thermochronological data, the Panormide platform was tectonically buried beneath the Alpine Tethys accretionary wedge during the Langhian-Early Tortonian (Dewever et al., 2010; Di Paolo et al., 2014). However, the complete lack of recognized metamorphism affecting the African units is in favor of a limited underthrusting of the margin as confirmed by the low burial depth estimation (< 4 km) of the Panormide Cretaceous limestones outcropping in the Madonie Mounts (Dewever et al., 2010).

During the late Tortonian-Early Pliocene time (Figure 4), deep-seated thrusting involved the ~ 1-2 km thick platform and basinal units. It led to wide syntectonic marine deposits at the footwall of large thrusts and ramp anticlines, interfering with the previously thrusted nappes of the accretionary prism (e.g., Avellone et al., 2010; Barreca and Maesano, 2012; Barreca and Monaco, 2013; Gugliotta et al., 2014; Barreca, 2015; Avellone et al., 2019). For instance, above the basinal Mt. Judica successions, thrusting of Numidian Flysch slices accompanied by synkinematic sedimentation led to a maximum burial depth of ~ 3 km during the Middle Miocene, before being exhumed in the Upper Miocene-Pliocene (Di Paolo et al., 2012). The deepening and hardening of the basal detachment are here attributed to the down-going Hyblean promontory. Acting as an indenter (Figure 5a to 5d), it forced the wedge to overcome a subcritical state by thickening during the Late Miocene-Early Pliocene with vertical growth accommodated by anticlinal stacks, out-of-sequence thrusting and tectonic imbrications (Di Paolo et al., 2012, 2014).

II.2.3 – *African margin paleogeography*

The Panormide platform only outcrops in northern Sicily, in the Palermo and Madonie Mounts (Figure 2, Figure 5a and 5c), but was recognized at depth in central-eastern Sicily in seismic profiles and wells (e.g., Bianchi et al., 1987; Bello et al., 2000; Finetti, 2005). It constitutes a key tectono-stratigraphic Sicilian unit because of its frontal position relative to the African paleomargin and early involvement in the SFTB. However, some studies suggested that its position relative to the Imerese basin could be inverted, meaning that the ATW first overthrusted the Imerese deep-water units prior to its overthrusting above the Panormide platform (Catalano and Di Maggio, 1996; Catalano et al., 2000; Catalano al., 2011; 2013a, 2013b). This assumption is mainly based on the observation of Imerese units locally thrusting above the Panormide units in Eastern Sicily (Palermo mountains). Nevertheless, such relationship is readily explainable by means of a later local back-thrusting contact (Finetti, 2005). Field evidences in the Madonie Mounts (Figure 6a and 6b) clearly show, however, a generalized overthrusting of the Imerese by the Panormide platform (see also Barreca and Monaco, 2013 and references therein). On the southwestern flank of Mount Mufara, the Upper Triassic Mufara Fm. outcrops, and served as a major décollement level, as testified by its intense folding and shearing (Figure 6c and 6d). However, such overthrusting of the Panormide platform is difficult to date because most of the Imerese Numidian cover has been detached (Figure 4), except the lowermost Portella Colla member (NF_{PC}, Figure 6a and 6b).

Based on these tectonic relationships and on the recognized stacked Imerese-Sicanian deep-water units in central-eastern Sicily (Figure 5), including the fact that the Panormide units are only reported in northern Sicily (Figure 2 and Figure 6a), we conclude it is implausible that the Imerese were the first to accrete and then to overthrust the Panormide platform. Thus, as inferred in Figure 3, the ATW most probably encountered first the Panormide platform that was at the African margin front, as proposed in numerous paleogeographic reconstructions (e.g., Catalano and D'Argenio, 1978; Grasso et al., 1978; Oldow et al., 1990; Patacca and Scandone, 2007; Vitale and Ciarcia, 2013, 2019 and many others).

II.2.4 – ***Thick-skin basement tectonics***

Based on available field observations, geophysical soundings and tectono-stratigraphic analysis, most authors consider that the Sicilian orogen is associated to thin-skinned tectonics, at least up to the Late Neogene (e.g., Ghisetti and Vezzani 1984; Bianchi et al., 1987; Roure et al., 1990; Bello et al., 2000). The general tectonic style is controlled by the strong rheological contrasts localizing efficient décollement levels (Figure 4); within the Alpine Tethys accretionary wedge (varicolored clays), at the base of the Numidian series and beneath the Meso-Cenozoic cover of the African margin (Triassic marly limestones of the Mufara Fm., Figure 6b, 6c and 6d), providing the conditions for strong mechanical decoupling.

Based on seismic lines (Figure 5d and 5e) and subsurface Plio-Pleistocene basins geometry, deep thrusting possibly also involved the basement and sign the transition toward thick-skinned tectonics since the Late Miocene (Bello et al., 2000; Guarnieri et al., 2002; Finetti, 2005; Catalano et al., 2013a). An equivalent setting has been evoked in central-southern Apennines, where thick-skinned model involving deep-seated-thrusting of the thick Apulian platform (equivalent of the Hyblean-Trapanese platform), implies 4 to 5 times less crustal shortening than prior thin-skinned models (Torzer et al., 2002 and Butler et al., 2004). Although not detected in older seismic lines along eastern Sicily (Bianchi et al., 1987, Roure et al., 1990; Lentini et al., 1990) and rejected in the analogous situation of southern Apennines (Scrocca et al., 2005), the thick-skinned model is consistent with the tardive development of long-wavelength synformal structures such as the Gela Nappe (Catalano et al., 2013a; Gasparo Morticelli et al., 2015) and the uplift and exhumation of the inner part of the orogenic wedge (Di Maggio et al., 2017).

Although determining the role of basement tectonics in such subduction orogens is of strong interest to infer accurate shortening estimations (Tozer et al., 2002; Butler et al., 2004; Scrocca et al., 2005), reliable data to quantify the extent of the thick-skinned deformation in Sicily are lacking. Consequently, the length of the tectono-stratigraphic units in Figure 5 are very dependent on the interpreted deep tectonic style of the Sicilian belt, and might also vary with the profile position due to spatial length variations of paleogeographic domains. Unfortunatelly, it also implies that the amount of shortening is widely unknow (Van

Hinsbergen et al., 2020). Thus the present study does not attempt to restore precisely the previous profiles, but rather to test a generic cross-section that led to the general structure of the central-eastern Sicilian chain.

II.2.5 - *Oblique convergence*

Paleomagnetic data, structural field work and associated paleogeographic reconstructions revealed that, since the Middle Miocene, the SFTB developed under oblique convergence and experienced locally large scale clockwise rotation from 10° up to 100° (e.g., Channel et al., 1990; Oldow et al., 1990; Speranza et al., 2003, 2018; Monaco and De Guidi, 2006; Cifelli et al., 2007; Barreca and Monaco, 2013; Van Hinsbergen et al., 2020). During Plio-Pleistocene, dextral shearing and block rotations along northern Sicily has been attributed to the southeastern migration of the Calabrian subduction system (Guarnieri, 2004) inducing tearing within the SFTB (Barreca et al., 2016). Based on structural analysis and deep seismic interpretations, dextral strike-slip faults, trending NW-SE, have been identified and considered as the tectonic features expressing the tangential component of the deformation (e.g. Bianchi et al., 1987; Lentini et al., 1990; Barreca and Maesano, 2012; Barreca and Monaco, 2013; Guarnieri, 2004; Barreca, 2016). However, no major shear zones, cutting the SFTB, are recognizable on the general geological map (Figure 2), and in the numerous published geologic and structural maps either (Bigi et al., 1991; Napoli et al., 2012; Catalano et al., 2013a; Lentini and Carbone, 2014; Gasparo Morticelli et al., 2017) except possibly along the NW-SE Cefalu-Mt Judica line (Barreca et al., 2016). Moreover, as shown by recent detailed paleomagnetic studies, most of these dextral strike-slip faults only accommodated minor offsets (Monaco and De Guidi, 2006; Barreca and Monaco, 2013; Speranza et al., 2018). These observations strongly suggest that the obliquity of crustal convergence was distributed over the whole SFTB rather than being localized along NW-SE major tear faults. Diffuse shearing likely impacted the wedge but without dismembering the regional structure of the SFTB.

Based on these considerations, we assumed that the structural evolution of the SFTB can be investigated using a frontal convergence tectonic setting representing a curved trajectory (yellow line in the Figure 3).

II.3 - Sicilide nappes: remaining issues and hypothesis

While the first-order paleogeographic attributions of Ogniben (1960) are widely accepted, the location of varicolored clays characteristic of the "Sicilide" units (Figure 2) inside the forearc basin sequence (i.e., the Antisicilide Fm. intercalated between the Capo d'Orlando flyschs and the Floresta calcarenites) and at the front of the Gela Nappe remains unclear. Possibly because the weak rheology of this unit can serve as an efficient décollement level, several nappe thrusting episods have been usually evoked to explain the very wide extension of the "Sicilide" deposits in Sicily. This interpretation is often integrated on the reported geological cross sections from the literature (Figure 5a, 5d and 5e). Unfortunately, good quality outcrops are scarce, aside from those in the inner wedge that usually show evidences of intense folding of red, gray and green scaly clays (Figure 7a).

Recently, stratigraphic reassessments suggested that the far travelled Sicilide nappe is unlikely to have reached southern Sicily. According to Butler et al. (2019), the occurrence in southern and northern-central Sicily of varicolored clays beneath the Tortonian silico-clastic deposits (Licata and Terravecchia Fm.) and the lack of "Sicilides" unit in the Mt Judica area before the Tortonian precludes a large scale Sicilide nappe, at least in eastern Sicily. To account for the occurrence of varicolored clays far from the inner part of the Alpine Tethys accretionary wedge, they propose an alternative solution in relation with the Oligocene facies of the Mt. Judica basinal succession. Their hypothesis is to consider that the Sicilide-like facies in the Mount Judica area do not belong to the Alpine Tethys accretionary Wedge (ATW), but correspond to lateral facies variations of the top of the Meso-Cenozoic Imerese-Sicanian deep-water units. The assumption is that the "scaglia" facies of the Judica Meso-Cenozoic series (Carbone et al., 1990), an equivalent of the Oligocene thin-bedded cherty and marly limestones of the top-Imerese succession (Caltavulturo Fm.), can be confused with the deep-water "Sicilides" from the Alpine Tethys. Indeed, it is likely that equivalent depositional environments in the Alpine Tethys realm and within the deep-water African margin basins at that time may have led to similar deposits. Such hypothesis was also suggested in the similar southern Apennines setting, where the Late Cretaceous-Lower Miocene upper portion of the Lagonegro basin is thought to have detached, and misinterpreted as varicolored clays from the ATW (e.g., Scrocca, 2010).

To the North, the "Antisicilide Fm." is another long-forgotten enigma that hasn't been challenged by evoking tectonic transport. This formation is usually attributed to a backthrusted nappe of "Sicilide" units coming from the ATW retrowedge (e.g., Bonardi et al., 1980, 1996; Bigi et al., 1991; Corrado et al., 2009; Lentini and Carbone, 2014). However, several first order features in the Peloritani domain, and previously reported in Calabria (Cavazza and Barone, 2010), do not fit well with the backthrusted nappe hypothesis: 1) the decreasing thickness of this intercalated unit within the continuous forearc sedimentation (thinning landward from hundreds to tens of meters), 2) its wide extension (~ 40 km away from the present day accretionary wedge remnants) and 3) its extremely weak rheology often associated to surprisingly undeformed strata outcrops in the field.

Gravity-driven and channelized sedimentation at the frontal and rear part of the ATW are submarine processes that could reconcile the occurrence of Sicilide-like sediments far from the inner wedge (present day Nebrodi mountains). Such processes have been evoked by several authors for the Alpine Tethys remnants in the Calabro-Peloritani forearc and the central-sicilian foredeep settings (e.g., Ogniben et al., 1953; Ogniben, 1955; 1962; Beneo, 1956; Flores, 1959; Rigo de Righi, 1956; Broquet, 1968; Amodio-Morelli et al., 1976; Görler, 1978; Kezirian et al., 1994; Patterson et al., 1995; Cavazza et al., 1997; Cavazza and Ingesoll, 2005; Grasso et al., 2001; Cavazza and Barone, 2010), but this scenario is still facing opposite interpretations describing these units as tectonically transported (e.g., Roure et al., 1990; Bello et al., 2000; Catalano et al., 2013a; Lentini and Carbone, 2014; Van Hinsbergen et al., 2020) or belonging to the pre-kinematic foreland series (Butler et al., 2019).

Considering wedge dynamic response to basal décollement geometry and friction changes, the Late Burdigalian “Antisicilide” Fm. could sign a collision-related instability affecting the ATW triggered by the onset of the African transitional crust subduction (Cavazza et al., 1997; Grasso et al., 2001; Cavazza and Barone, 2010). The Antisicilide unit (Figure 7b, 7c and 7d) is essentially made of a sheared reddish-greenish to gray clayed matrix (Cavazza et al., 1997) containing blocks of variable dimensions and ages ascribed as Paleogene calcareous-marly turbidites (Polizzi Fm.) and Oligocene-Early Miocene quartzarenites (Numidian Flysch). In central Sicily, similar facies are found (Figure 8c), with exotic blocks of various lithologies, ages and sizes within the scaly varicolored clays, and ascribed in geological maps as tectono-sedimentary mélange (Tortorici et al., 2014; Carbone et al., 1990, 2011). In both cases, a striking observation is that the marly clasts are slightly or not deformed (Cavazza et al., 1997) as well as most of the blocks contained in the mélange (Figure 7b, 7c and Figure 8c). In the corresponding outcrops, some strata appear disturbed by plastic deformation (Figure 7d) or strata dismembering (Figure 8a and 8b), at the origin of the block-in-matrix fabric (Larroque, 1993),.

In the Apennines similar Sicilide units were described as reworked sediments by gravity-driven processes (e.g., Critelli, 1999; Festa et al., 2010). Such chaotic lithologies were widely analyzed in the past decades to infer the characteristics of mélanges whether they derived from tectonic or sedimentary processes (e.g., Pini, 1999; Bettelli and Vannucchi, 2003; Vannucchi and Bettelli, 2010; Festa et al., 2010; 2012; 2019). According to these studies, the block-in-matrix fabric can be found in both context, but the lack of structurally ordered fabric (Figure 7 and Figure 8) and the absence of tectonic contact do not favor a tectonic transport. The chaotic "Sicilide" and "Antisicilide" mélanges could then testify of gravity-driven mechanism ranging from large-scale and proximal mass wasting (olistostromes), to distal partly channelized deposits such as debris flows (Figure 7b, 7c, 7d and Figure 8a, 8b and 8c). These mélanges associated to the varicolored clays from the "Sicilide" units were described all over southern and central Sicily, in the Caltanissetta area (Tortorici et al., 2014), the Judica mountains (Carbone et al., 1990), Agrigento (Decima et al., 1972) and Licata (Grasso et al., 1997). These maps report up to kilometer-scale exotic blocks, the age of which ranges from Upper Cretaceous up to the Early Miocene. For instance, hundreds of meters blocks of Polizzi marly and turbiditic limestones of Eocene age are embedded in the varicolored clays from the south of the Villarosa Lake to Mount Marcasita north of Caltanissetta (Tortorici et al., 2014).

Moreover, associated to these significant inferred mass-wasting events, coeval thinner deposits with limited clasts content are also expected to deposit, in more distal environments through turbiditic systems. Indeed, North of Licata (Southern Sicily), units that were mapped as varicolored clays (Grasso et al., 1997) do not show the typical variegated facies (as shown in Figure 7a), but grayish-brownish unstratified and poorly consolidated clays (Figure 8e and 8f).

In the nearby offshore Leone 001 well (Figure 8d), a ~ 130 m thick layer of these sediments were recognised at ~ 2200 m depth, intercalated within the deep-water Licata laminites without any reported tectonic contacts. These varicolored clays are also attributed to the substratum of the Langhian-Tortonian Licata Fm. in southern Sicily (Grasso et al., 1997; Lickorish et al., 1999; Basilone et al., 2018; Butler et al, 2019). If this varicolored clays mélange was belonging to a tectonic nappe, its emplacement should date back to the Middle Miocene, long before the Late Miocene-Pliocene inferred arrival of the deformation front in this area (Lickorish et al., 1999). Thus, it is implausible to associate such sediments to tectonic transported mélanges, while gravity-driven sediment flows are likely processes to explain their wide extension and long transport distance.

Moreover, as suggested above, these sudden intercalations within the continuous forearc ("Antisicilide" units) and foreland (far travelled "Sicilide" units) sequences should be related to pulses of erosion and mass sediment transport associated to tectonically induced wedge instabilities (Cavazza et al., 1997; Grasso et al., 2001). These interpretations are investigated in light of model outcomes in the section III.

II.4 – Possible restoration of the eastern SFTB

To model experimentally the tectono-stratigraphic evolution of the eastern Sicilian Fold and Thrust Belt (SFTB), a conceptual reconstruction model is needed to build the initial state of the experiment and provide realistic boundary conditions to control its dynamics. This reconstruction aims to integrate the review and the most recent literature outcomes as well as the argued hypothesis regarding the intercalation of Sicilide-like units within the forearc and foredeep/foreland sedimentation (Figure 3 and Figure 9). The proposed scenario includes: a qualitative paleogeographic restoration (Figure 9) along the inferred trajectory of accreted units (yellow line, Figure 3), and a tectono-stratigraphic timetable representative of the central-eastern Sicilian belt evolution, split in six major phases describing the SFTB dynamics over the last 30 Myr.

1. The onset of the accretionary wedge construction dates back to the Oligocene with the initiation of slab roll back and the **accretion of Alpine Tethys sedimentary cover** at the front of the Calabro-Peloritani domain (Figure 9a), still attached at that time to the Corso-Sardinian block (Faccenna et al., 2004). This stage is evidenced in the field by the Molassic Piedimonte Fm. (top of the Mt. Soro subunit), and then overlain by the Upper Oligocene-Early Miocene forearc deposits of the Capo d'Orlando Fm. (Belayouni et al., 2006).

At the same time, the Numidian Flyschs started depositing widespread both as trench-fill deposits on the continental slope of Panormide domain (e.g., Nicosia and Mt. Salici subunits) and in the Imerese foreland basin, while in the vicinity of the Hyblean promontory glauconitic-bearing sandstones and clays were sedimented.

2. During the Lower Miocene (Figure 3a), the propagation and progressive building of the Alpine Tethys wedge (ATW) occurred above a incompletely oceanized Alpine Tethys crust (as testified by the lack of ophiolitic material incorporated into the accretionary wedge) or underwent significant tectonic erosion and subsequent material output in the subduction channel. Then, the prism front encountered with the base of the African paleomargin slope (Figure 9b), inducing significant internal readjustment to adapt the wedge taper to new geometric and basal friction conditions.

We associated and dated this deformation phase, mainly affecting the rear part of accretionary wedge, to the **deposition of the "Antisicilide" unit** during the Burdigalian (Figure 3b and Figure 9b). Indeed, this unexpected deposit (c.f. II.3) appears conformably intercalated in the regular forearc sedimentation (Cavazza and Barone, 2010) between the silico-clastic Capo d'Orlando flyschs (Hercynian crystalline source) and the bioclastic calcarenites of the Floresta Fm. (shallow-water carbonates source). The deposition of the Antisicilide signs, then, a significant source shift in the forearc basin likely associated to submarine gravitational processes reworking AT material exhumed in the retrowedge through backthrusting.

Meanwhile, Numidian Flyschs and glauconitic silicoclastic sediments, probably also including some reworked units from the ATW, continue to be deposited in the active foreland basin, at the wedge front and in the inner part of the ATW with the Peloritani-fed Reitano flyschs (de Capoa et al., 2004; Puglisi, 2014).

3. From the Early Langhian (Figure 9b), the **Panormide unit was progressively underthrusted** beneath the ATW while the sedimentation in wedge-top depocenters and in the forearc basin continued (Reitano flysches and Floresta calcarenites respectively). The Numidian Flysches graded up into marly levels at the wedge front and in the foredeep (Gagliano, Castelbuono and Tavernola marls), together with glauconitic calcarenites southward (Corleone calcarenites).

4. During the Serravalian-Early Tortonian time (Figure 3b and 3c), the Alpine Tethys wedge (ATW) likely underwent a second dynamic equilibrium change probably related to underplating of deep units and anticlinal stacking processes affecting the underthrusted Panormide platform. In response to **wedge shortening and thickening, another Sicilide units reworking pulse, controlled by gravity-driven and erosional sedimentary processes, likely occurred,** depositing Sicilide-like facies in the Imerese-Sicanian basin. This heterogenous unit is overlaid to the north, or intercalated (Grasso and Pedley, 1988), by the discontinuous Serravalian-Early Tortonian sandy clays (Castellana Sicula Fm.) and the Late Tortonian silicoclastic sediments of the Terravecchia Fm. and its southward equivalent, the Licata Fm. During this period, the inner wedge sedimentation turned back to a terrigenous sedimentation above the Peloritani basement indicating that a wide portion of the top of the orogenic prism was emerged at that time.

5. In the Upper Miocene (Figure 3d), **Deep-seated thrusting** migrating southward progressively incorporated the Imerese-Sicanian units into the orogenic wedge, forming piggy-back basins such as the Corvillo and Mandre synclines in central Sicily (e.g., Grasso and Pedley, 1988; Barreca, 2015) and thrust-controlled Messinian depocenters such as the Caltanissetta basin (Butler et al., 2015).

6. The last major tectonic phase probably involved Plio-Pleistocene **deep thrusting of the basement** (i.e. older than late Triassic) that favored the formation of piggyback basins (Figure 5d and 5e, after Bello et al., 2000; Catalano et al., 2013a), delimited by in-sequence and out-of-sequence conjugate thrust and backthrust systems. After the brief Messinian infilling, the Lower Pliocene marine transgression covered most of the southern part of the wedge with marly-limestones of the Trubi Fm., which then turned to subaerial continental sediments in the thrust-top basins and the Gela foredeep. In this context, the Centuripe syncline was filled by > 400 m thick Lower-Middle Pliocene marine sediments as well as its southwestward equivalent in the Caltanissetta basin (e.g., Tortorici et al., 2014; Imera syncline, Figure 6e). This later thick-skinned tectonic event in northern Sicily, along with the slab detachment that likely induced a generalized uplift phase according to the model of Wortel and Sparkman, (2000), progressively raised the whole orogenic wedge above sea level during the Quaternary (Di Maggio et al., 2017).

III - Analogue modeling set-up and experimental procedure

To conduct an in-depth investigation of the deformation processes controlling the geodynamics of the SFTB and assess the relevance of the proposed evolutionary scenarios and new challenging hypothesis, we performed a series of analogue models based on the reviewed tectono-stratigraphic data and qualitatively restored geological cross sections (Figure 9). We favor the experimental approach because it can includes a set of complex boundary conditions that are difficult if not impossible to integrate jointly using numerical modeling (erosion and sedimentation, mechanical stratigraphy, tectonic inheritance, large crustal shortening, syn-orogenic flexure and adjustable subduction window). These complex and challenging experiments led to a set of models that can be compared to the natural case and largely help discussing the structure and evolution of the SFTB.

Analogue modeling has been already extensively used to investigate mountaing building processe (see review in Graveleau et al., 2012) such as; the role of décollement properties on deformation mechanisms and shape (critical taper) of orogenic wedges (e.g., Malavieille et al., 1984; Davis et al., 1983; Dahlen et al., 1984; Dahlen, 1990; Burbidge and Braun, 2002), the interactions between tectonics and surface processes (e.g., Malavieille et al., 1993; Mugnier et al., 1997; Bonnet et al., 2007; Graveleau et al., 2008; Cruz et al., 2010; Malavieille, 2010), the impact of décollement levels and ductile rheologies (e.g., Davis and Engelder, 1985; Konstantinovskaya and Malavieille, 2005; 2011; Costa and Vendeville, 2002; Ruh et al., 2012), the effect of series thickness (e.g., Huiqi et al., 1992; Marshak and Wilkerson, 1992) or the role of structural inheritance (e.g., Bonnet et al., 2008; Bonini et al., 2012; Granado et al., 2017; Balestra et al., 2019). In some cases, the dynamics of real orogens, such as the Western Alps (Bonnet et al., 2007) or the Taiwan orogen (Malavieille and Trullenque, 2009; Malavieille et al., 2019), have also been successfully modeled.

III.1 - Experimental set-up, scaling and analogue materials properties

The experiments were conducted under normal gravity in a 2D sandbox apparatus (Figure 10) similar to the one developed by Bonnet et al., 2007 and Malavieille, 2010. The device is 0.25 m wide, 0.4 m high and 2 m long. It is constituted by an aluminium structure supporting a bended 2 cm thick PVC plate, simulating the subducting lower plate and a rigid vertical backstop, simulating the undeformable part of the upper plate (Figure 10). The device is equipped with two lateral glass walls allowing for direct observation of model evolution in cross-section and in perspective view. The experimental set-up enables infill of additional material (sedimentation) or manual erosion during the experiment evolution and allows large crustal shortening simulation (> 250 cm).

A triangular-shaped backstop representing the strong crust of the upper plate Calabro-Peloritani block is positioned above the tilted lower plate model base with an adjustable subduction window at its back to control the amount of material output during the experiment (Figure 10). Indeed, the balance between a gradually growing wedge dominated by frontal accretion and a wedge deforming by out-of-sequence thrusting and basal accretion is mainly dependent on the ratio of material input versus material output (Gutscher et al., 1996, 1998). A motor pulls, along the basal plate and beneath the backstop, a 25 cm wide inextensible Mylar sheet (armed with carbon-kevlar fibres) representing the plunging lower plate. Over the pulled sheet, layers of analogue granular materials mimic the sedimentary cover of the African-type paleo-margin and Alpine Tethys oceanic basin at the Oligocene time. The structural inheritance and basement topography of the margin is accounted by using rigid or highly cohesive units above the Mylar sheet (Figure 10). Ahead the backstop front and fixed beneath to the PVC lower plate base, a jack is used to pull down the model base to impose a first-order tectonic flexure beneath the growing orogenic accretionary wedge.

Model scaling is based on a length ratio between nature and model of about $0.5\text{-}1\text{x}10^5$ meaning that 1 cm in the model represents 1-2 km in the nature. The Mylar sheet length (~ 400 cm) allows a total shortening of > 250 cm, representing ~ 350-400 km of plate convergence.

The basal friction in such settings can be adapted from “low” to “high” depending on the roughness of the basal surface and the overlying materials (Malavieille et al., 2016). “High” basal friction ($\mu_b \approx 0.6$) is obtained when granular materials are in contact with a rough surface such as an abrasive sand paper; “low” basal frictions ($\mu_b \approx 0.2$) are obtained with glass microbeads deposited above a smooth surface. Although such parameters are poorly constrained in nature, the critical wedge theory (Davis et al., 1983; Dahlen et al., 1984) predicts well the effect of the basal décollement strength on thrusts dip and the critical taper of the wedge. Hence, the basal friction in the model is mainly selected to: (1) allow the formation of a low-tapered (< 6-7°) oceanic accretionary wedge (equivalent to the Alpine Tethys or the current Calabrian and Hellenic accretionary wedges), (2) let the continental inherited basement topography of the lower plate subduct under the sedimentary wedge before its possible stacking at depth by basal accretion (e.g., Bello et al., 2000; Catalano et al., 2013a) and coeval exhumation.

Three kinds of granular materials (sand, glass microbeads and silica powder) deforming according to the Mohr-Coulomb theory and widely used in previous experimental studies (e.g., Bonnet et al., 2007; Malavieille et al., 2016) are chosen as analogues of the contrasted natural tectonic and stratigraphic units represented in the SFTB. The quartz sand has a grain size of 150-300 µm, a bulk density of 1690 kg/m^3, a coefficient of internal friction $\mu_0 \approx 0.57$ and a cohesion $C_o \approx 50\text{-}100$ Pa. At room temperature and ~ 50% hygrometry, the weak layers and décollement levels are simulated with glass microbeads (grain size ≈ 90-150 µm) whose coefficient of internal friction and cohesion are significantly lower than those of the quartz sand ($\mu_0 \approx 0.44$ and $C_o \approx 10\text{-}30$ Pa). A mixture of quartz sand and cohesive silica powder ($C_o \approx 150$ Pa) is used to model the strongest lithostratigraphic units such as the African continental basement, the Calabro-Peloritani block and the carbonate platform units (Panormide, Trapanese-Saccense-Hyblean). A new specific material is used to simulate the varicolored clays of the Alpine Tethys wedge and to account for the major décollement level that allowed its thrusting above the African margin. This material, commercialized as "kinetic sand", is made of 98% of sand and 2% of Polydimethylsiloxane (PDMS). It has a visco-plastic behavior and presents the interesting property to deform with a very low basal friction when in contact with the smooth basal Mylar sheet.

Model monitoring is ensured by two high resolution camera (~ 120 µm per pixel) taking pictures on one side of the experiment every 2.5 mm of shortening. A sub-pixel correlation algorithm (Van Puymbroeck et al., 2000) extracts the instantaneous displacement field allowing quantitative measurements of model dynamics (kinematics and mechanics).

III.2 – Initial stage, boundary conditions and modeling procedure

The initial setup, presented in figure 10, is based on the literature synthesis and a first set of preliminary analogue models. It takes into account the mechanical stratigraphy (Granath and Casero 2004) inherited from the margin structure and stratigraphy. Although the model stratigraphy is a major simplification of the natural case, it mimics the main lithostratigraphic units of Sicily both in terms of thicknesses and rheological contrasts. The upper part of the backstop, representing the Peloritani crust, is made of a highly cohesive mixture (quartz sand 80%, silica powder 20%) as well as the basement of the platformal and basinal units of the modeled african margin (1-2 cm beneath the Panormide and < 1 cm beneath the Imerese-Sicanian analogue). Over the structured basement, the ~ 10 mm thick platform is made of a cohesive mix (quartz sand 90%, silica powder 10%), and the 10-15 mm to 0 mm basinal sequence is represented by a lower cohesive unit (quartz sand 100%). At their base, these units have a ~ 2 mm thick microbeads layer insuring a strong mechanical decoupling with the basement (equivalent to the Upper Triassic Mufara formation). The northeastern part of the Hyblean promontory is here represented by a 3-4 mm thick cohesive mix on which the basinal unit thins. The Alpine Tethys-like unit is made of a basal, 5 mm thick, visco-plastic "kinetic sand" layer, and an upper layer made of sand (moderate to low cohesion) that thins from the backstop front to the modeled deep-water domain (~ 30 mm thick to 0). The basal layer has a very low coupling with the model base and allows the formation of a low-tapered oceanic accretionary wedge (< 6-7°). Considering the low rigidity of the ATW material, a required mechanical constrain to overthrust the African margin slope as far as possible is to maintain very low basal friction conditions. To do so, the gradual ocean-continent transition is simulated by a long and low-angle margin slope geometry made of 2 rigid blocks fixed to the Mylar sheet (4 mm and 8 mm thick). These blocks, equivalent to tilted continental basement units inherited from the rifting, have a low surface friction producing a strong decoupling between the basement and its Sicilide-like cover extending up to the main margin front (Panormide platform). This low friction ramp allows the progressive building of the low-tapered accretionary wedge and the early underthrusting of the margin basement front.

Synkinematic sedimentation is made of glass microbeads layers that have low cohesion and friction properties, such as poorly diagenetized and weak marine sediments. An exception is made for the forearc deposits (made of quartz sand layers) that received a significant amount of clastic deposits (e.g., Capo d'Orlando, Floresta calcarenites).

The lack of a well-constrained timetable, describing shortening, sedimentation, erosion and tectonic processes evolution during the SFTB building, makes the model tectono-stratigraphic evolution dependent on the chosen erosion and sedimentation rates. Therefore, two possibilities emerge to converge toward a realistic evolution. When the data from the literature testify of major sediment supply from domains that are not represented in the model (for instance, the Numidian Flysch), we apply sedimentation rate that combined with the fixed shortening rate provides sediment thicknesses equivalent to the ones inferred from field and geophysical constrains (Figure 4 and Appendix A, up to ~ 1000-2000 m for the Numidian Flysch). However, when poor constraints exist (e.g., Early Miocene syntectonic wedge-top deposits, reworked Alpine Tethys sediments from the ATW to the trench/foreland depocenters), we favor sedimentation and erosion rates that respect the theoretical model evolution (see section II.4). For instance, erosive phases are locally applied when the orogenic wedge reaches critical slopes (> 10-15°) or rises above a fixed sea level reference (Figure 10). During significant uplift phases, or critical states of equilibrium within the prism, major sedimentation phases are then expected unless evoking sediment transport sub-parallel to the trench such as the Numidian turbidites. Moreover, as deduced from seismic profiles, the thickness of the orogenic wedge is about 10-15 km in central-northern Sicily (e.g., Bello et al., 2000; Catalano et al., 2013a), indicating that significant amount of flexural subsidence (~ 5-10 km) possibly occurred during the wedge growth, maintaining it mostly underwater. Hence, we adjust the subsidence of the lower plate (~ 14 mm equivalent to ~ 2 km in nature) to account for the orogenic load and provide a sufficient tectonic accommodation space. The plate is pulled downward at the tip of the Peloritani-like backstop producing subsidence over the first ~ 120 cm. However, the major component of the subsidence is provided by the initial plate flexure (Figure 10), that combined to the imposed subsidence, led to a final wedge thickness of ~ 10 cm (equivalent to 10-15 km in nature).

Material output boundary condition is a key parameter controling the mass flux balance of the orogenic wedge. When the subduction channel is reduced, the tectonic accretion is maximum. On the other hand, a thick subduction channel favors long-living out-of-sequence thrusting and thus reduces the accommodation of shortening by frontal accretion (Gutscher et al., 1996, 1998). Our experiments start with no or very limited material output and progressively goes up to ~ 1 cm of subduction channel opening favoring the underthrusting of the stretched African continental margin (represented by the rigid basement blocks).

The convergence rate is fixed to 5 mm/min and stopped every 50 mm of displacement. These cycles allow, during each break, to perform: (1) the potential subsidence of the model base by increments of ~ 2 mm, (2) the erosion (up to 5 mm) when critical conditions are reached, and (3), the sedimentation of synkinematic material (< 1 mm up to 2-3 mm. Because the convergence rate is fixed and the model evolution velocity-independent, we use a ratio between the convergence and the amount of sedimentation, erosion/exhumation or subsidence to define the corresponding sedimentation, erosion or subsidence "rates". Hence, these rates capture the quantitative model evolution through time and serve to described and analyze its dynamics.

$$\boldsymbol{R_{SeC}} = \textit{sedimentation (mm) / convergence (mm)}$$

$$\boldsymbol{R_{ErC}} = \textit{erosion (mm) / convergence (mm)}$$

$$\boldsymbol{R_{ExC}} = \textit{exhumation (mm) / convergence (mm)}$$

$$\boldsymbol{R_{SuC}} = \textit{subsidence (mm) / convergence (mm)}$$

$$\boldsymbol{R_{OuC}} = \textit{output (mm) / convergence (mm)}$$

A series of 11 test models have been performed to determine first-order parameters and boundary conditions controlling the structure and tectonic evolution of the Sicilian orogenic wedge. They converge toward a representative model of the Sicilian Fold and Thrust Belt. These experiments are not described in the following section that focuses only on the last and most representative experiment.

III.3 – Results from analogue modeling

In the followings, we present the results of the most relevant analogue model simulating the Sicilian belt evolution (Figure 11, 12, 13, 14 and Appendix B for a complete video of the model). This experiment is the one that best match the available geological and geophysical observations and measurements (discussed further). The total convergence operated during this experiment is about 272 cm (~ 400 km). It is subdivided into 54 steps (t_0 to t_{54}) of ~ 5 cm of shortening.

In response to the tectonic evolution of the model, the erosion and sedimentation rates as well as their localisation evolve through time. During the first phases (from t_0 to t_{14}, 0-70 cm of convergence), when the oceanic accretionary prism (ATW) growth above the oceanic floor (t_{10}, Figure 11 and Figure 12), we apply: (1) a low sedimentation rate (t_{10}, Figure 13), both in the forearc and foredeep/wedge-top-basin domains (0.3-1 mm each 50 mm of convergence, R_{SeC} ~ 0.006-0.02), (2) no erosion and (3) low subsidence rate (R_{SuC} 0 to 0.01). Then, when the African margin front starts to be underthrusted beneath the ATW (from t_{14} to t_{22}, 70-110 cm of convergence), the coeval shortening and thickening of the wedge (t_{18} and t_{22}, overthrusting initiation of margin front step 1 and step 2, Figure 11 and Figure 12) produce slope instabilities and top-wedge emersion that imply: (1) higher sedimentation rate (up to R_{SeC} ~ 0.01-0.04), (2) initiation of subaerial erosion (t_{22}, Figure 9, R_{ErC} > 0.06) and (3) a sligth increase of the subsidence rates (R_{SuC} ~ 0.01). Quickly after the beginning of the convergence, a forearc basin develops between the (Peloritani-like) upper-plate block and the rear part of the wedge controlled by an out-of-sequence backthrusts system (t_{10}, t_{18} and t_{22}, Figure 11 and Figure 12).

During the oceanic subduction phase (0-70 cm of convergence, Figure 14a), the accretionary wedge mainly grows (Figure 14a) by frontal accretion and thickens by diffuse out-of-sequence thrusting, folding and compaction (~ 15%) within the wedge (t_{10}, Figure 11 and Figure 12). Despite maintained low basal friction conditions when the ATW reached the first structures of the African margin, the wedge dynamics is perturbated. . The underthrusting of gentle basement steps produce a series of widespread out-of-sequence backthrusting that propagate toward the backstop (Peloritani basement). The lengthening of the accretionary wedge progressively slow down (Figure 14a), partly replaced by diffuse internal deformation and a generalized thickening controlled by conjugated out-of-sequence thrusts and backthrusts (t_{18} and t_{22}, Figure 11 and Figure 12). Moreover, along with the later intra-wedge pop-ups, small piggyback basins form above the wedge and are partly filled by syntectonic sedimentation (t_{18} and t_{22}, Figure 13).

At a more advanced stage of the experiment, the Panormide-like platform unit is underthrusted beneath the ATW (t_{25} and t_{28}, Figure 11 and Figure 12). Although the top of this cohesive unit is made of synkinematic glass microbeads with a low internal friction, the landward tilting of the wedge main décollement following the African margin slope and the increase of the basal friction induce a major evolution of the state of dynamic equilibrium of the ATW. In response to this major wedge shortening (Figure 14a) and thickening phase (t_{25} and t_{28}, Figure 11 and Figure 12): (1) larger sedimentation rates are applied in the foredeep (t_{25} and t_{28}, Figure 13, R_{SeC} ~ 0.02-0.08) to correlate with (2) the onset of significant erosive events (R_{ErC} ~ 0.10-0.15) reworking material from the wedge top (emersion) and its flanks (critical slopes), and (3) moderate subsidence rates (R_{SuC} ~ 0.01) persist to accommodate increasing orogenic loading. The major backthrusting and uplift of the retrowedge (t_{25} and t_{28}, Figure 12b) lead to its emersion activating potential gravitational instabilities that justify the deposition of reworked wedge material, in the forearc basin (t_{25} and t_{28}, pinkish deposit equivalent to the "Antisicilide", Figure 11). This phase is accompanied by important out-of-sequence thrusts and backthrusts (t_{25} and t_{28}, Figure 11 and Figure 12a) that localize inner-wedge pop-ups inducing a significant shortening (20-30 cm, Figure 10b) and exhumation (R_{ExC} ~ R_{ErC} ~ 0.10-0.15, t_{25} and t_{28}, Figure 12b and Figure 13) that start consuming the Alpine Tethys accretionary wedge.

The basal décollement is then transferred to the foreland (Panormide-like platform), even though a significant out-of-sequence thrusting continues to underthrust the platform beneath the Alpine Tethys wedge (t_{31} and t_{37}, Figure 11 and Figure 12). Regarding to this changing deformation style: (1) significant sedimentation rates are maintained in the foredeep (t_{31} and t_{37}, Figure 13, R_{SeC} up to 0.08) in correlation with (2) major erosive pulses (t_{31} and t_{37}, Figure 13, R_{ErC} up to 0.15), and (3) moderate subsidence rates (R_{SuC} ~ 0.01) that sign the initiation of continental subduction and the associated increasing compressional regime. The subduction of the margin front, in particular the 4 mm and 8 mm steps 1 and 2 (Figure 10), is also accompanied by the opening of the subduction channel to let the rigid basement getting out of the system (R_{OuC} ~ 0.1-0.2). Along with the frontal accretion of foreland units due to its décollement at the platform base, a major forelandward out-of-sequence thrusting of the Alpine Tethys wedge overthrusts the platform (t_{31} and t_{37}, Figure 11 and Figure 12). This is why, although the deformation front (DF) is now separated from the Alpine Tethys front (ATF), they both stay close to each other (Figure 14a). The ATW is still active but gently moves back because of its erosion and inner-wedge shortening, while the DF maintains a global steady-state by oscillating between fast advances (new frontal thrusts) and moderate backward migration (underthrusting beneath the Alpine Tethys wedge). This structural shift toward frontal accretion tectonics is associated to an exhumation of the inner and frontal parts of the Alpine Tethys wedge (t_{31} and t_{37}, Figure 12b and Figure 13) that explains why significant reworked sediments from the ATW are deposited in the foredeep (t_{31} and t_{37}, pinkish deposit, Figure 11). From that stage, the important cumulated out-of-sequence backthrusting and uplift of the rear-wedge led to its emersion, allowing sedimentation only in the most internal part of the backstop.

Following the complete décollement of the Panormide platform and its underthrusting beneath the ATW, the Imerese-Sicanian-type basinal units are offscrapped and strt to accrete at the front of the orogenic wedge (t_{41} and t_{44}, Figure 11 and Figure 12): (1) Lower sedimentation rates are applied in the foredeep and above the frontal piggy back-basins (t_{41} and t_{44}, Figure 13, $R_{SeC} < 0.02$), along with (2) a moderate to low erosion rates ($R_{ErC} < 0.1$), and (3), no subsidence to avoid a complete subduction of the platform unit beneath the backstop. In addition to the subsidence stop, the subduction channel that was opened to allow the subduction of the continental margin front is also progressively closed. The orogenic wedge quits a phase of underthrusting and underplating of the Panormide-like platform and shifts toward frontal accretion of basinal units and slow underplating of foreland units (t_{41} and t_{44}, Figure 11 and Figure 12). It results into a gentle exhumation of the inner-wedge (t_{41} and t_{44}, Figure 13). A gradual regrowth of the wedge is recorded (advancing DF, Figure 14a) while the ATW continues to shorten. The exhumation is at that stage mainly localized at the front of the chain (t_{41} and t_{44}, Figure 12b and Figure 13) and the decreasing ATW erosion is accompanied by a return toward foredeep sedimentation with a limited supply from the ATW (t_{41} and t_{44}, Terravecchia and Licata equivalents, Figure 11).

Finally, the thick Hyblean platform is underthrusted beneath the fold-and-thrust belt and the basal accretion of the basement is still active, leading to: (1) a moderate to low sedimentation rate in the foredeep and the frontal piggy-back basin (t_{53}, Figure 13, $R_{SeC} \sim 0.02$) and (2), a major erosive phase with a maximum exhumation localized above the basal accretion of the basement ($R_{ErC} > 0.2$). This major erosive phase (t_{53}, Figure 13) is probably overestimated in the inner wedge due to an incomplete subaerial erosion in the preceding model steps (< t_{53}) but it is consistent with an increased exhumation at the end of the convergence (t_{53}, Figure 12b, R_{ExC} ~ 0.2) in response to the Panormide platform underthrusting and the inner uplift related to basal underplating (t_{53}, Figure 11 and Figure 12). Again, the increased basal slope associated to the underthrusted platform increased the critical taper of the wedge, forcing it to shorten and thicken by backthrusting events as well as long out-of-sequence forelandward thrusts. At this stage, the exhumation and emersion of the inner-wedge keep supplying the foredeep and piggyback basins with wedge-reworked materials.

IV - Interpretation and discussion

Our model succeeds in reproducing the general structure and morpho-tectonic characteristics of the Sicilian Fold-and-Thrust Belt (SFTB) providing, then, insightful mechanical constraints on the development of the chain. Model evolution also provides straightforward qualitative and quantitative observations to investigate the couplings between orogenic wedge dynamics and associated tectono-sedimentary processes. The following discussion focuses on the model outcomes concerning: 1) the controversial origin of forearc and foredeep deposition of Alpine Tethys like units, 2) the deformation history of the Panormide platform, and 3) the main tectono-sedimentary evolutionary phases of SFTB.

As for any experimental results, extrapolation of the model to nature should be done taking into account the imposed mechanical and kinematical boundary conditions as well as initial model geometry and structure:

- The modeled convergence is purely orthogonal to the African margin while in nature an oblique component triggered the rotation of the detached African margin units (e.g., Channel et al., 1990; Oldow et al., 1990; Speranza et al., 2003, 2018; Monaco and De Guidi, 2006; Cifelli et al., 2007; Barreca and Monaco, 2013; Van Hinsbergen et al., 2020). According to tectonic observations and paleogeographic reconstructions, we consider that this oblique kinematic component is distributed in space and time all along the SFTB rather than being localized along major long-living strike-slip faults (see section II.2.5). Consequently, model evolution should be compared to the reconstruction of the SFTB along a curved cross-section following the reconstructed trajectory of the different SFTB tectonic units, as illustrated by the diffuse distorsion in Figure 3 (yellow line).

- The velocity discontinuity at the rigid backstop tip influences the localisation of the retrowedge backthrust systems, leading from the middle of the experiment (~ t_{30}) to an over-exhumation of the Peloritani basement. Consequently, no forearc deposits over the Peloritani front and Alpine Tethys Wedge (ATW) are preserved at the end of the modelisation. While backthrusting could be a significant process accommodating shortening in Western Sicily (Albanese and Sulli, 2012), or in the nearby Calabrian wedge (Van Dijk et al., 2000), only minor north verging thrusts were identified in central-eastern Sicily (e.g., Sulli et al., 2019). The back-arc extension tectonics is not included in the models although it started affecting the rear part of the ATW since the Serravalian (Lentini et al., 1995; Di Paolo et al., 2014 and citation therein) and more recently from the Pliocene (Monaco et al., 1996).

- The evolution of the subduction interface geometry, simulated by imposing a flexural subsidence to the model, is limited (~ 14 mm, corresponding to 2-3 km in nature) and only partly account for the foreland flexure migration associated to slab rollback. Although it does not have a significant impact on the orogenic wedge shape and mechanics, it controls the timing of the wedge emersion and, then, the initiation of sub-aerial erosion and sediment redeposition in the foredeep.

- The rheologies of the SFTB main lithostratigraphic units are only roughly constrained, and thus, potentially inaccurate or oversimplified in the model. For instance, the syntectonic Numidian Flyschs are simulated using a weak granular material to account for the cohesive (~ sandstone facies) and weaker (~ clayey facies) alternations favoring the décollement of the Numidian cover. However, the degree of weakness (cohesion) compared to the other lithostratigraphic units remains unknown.

- Another limitation concerns the basal friction, i.e. the strength of the ATW basal décollement, which is commonly overstated in sandbox analogue models (Huiqi et al., 1992), therefore curbing the deformation front propagation (e.g., Davis et al., 1983; Dahlen et al., 1984). Although we succeeded in building a low-tapered oceanic accretionary prism from t_0 to t_{22}, using a specific analogue material, the final orogenic wedge still exhibits high-angle thrusts and a higher taper compared to nature because the décollement levels below and above the African Meso-Cenozoic units are not weak enough.

- In our experiments, we only represent the very upper part of the African continental basement (< 2 cm, equivalent to 2-4 km in nature), limiting then the role of the basement tectonics. Consequently, small basement flakes are simulated at the end of the model evolution, rather than thick units controlled by late deep-seated crustal faults (e.g., Bello et al., 2000; Catalano et al., 2013a). Due to the lack of reliable data concerning potential basement fault geometries at depth, we decide to only simulate the uppermost part of the African basement geometry constraining the basins and platforms architecture (Figure 10), as inferred from the general cross sections presented in Figure 9.

IV.1 - Forearc and foredeep Alpine Tethys "mélange"

As underlined in the section II.3, the occurrence of Alpine Tethys units (Figure 2) intercalated in the forearc (“Antisicilides”) and foreland sedimentation (“far travelled Sicilide”) have strong implications on the reconstruction of the SFTB tectonic evolution. First of all, the analogue model evolution (Figure 11) points out a limited thrusting of the ATW both on the African margin and on the Peloritani-like backstop. Although the décollement levels are likely not as efficient as in nature, the complete overthrusting of the African platform and basin before the Early-Middle Tortonian (< t_{40}) is not consistent with the modeled accretionary wedge dynamics. Indeed, since its encounter with the first bathymetric highs of the OCT and then the Panormide platform front (step 3 in Figure 14a) during the Lower-Middle Miocene, the Alpine Tethys Wedge front gradually retreat toward the Peloritani backstop due to internal deformation induced by changes in main décollement geometry and friction properties.

In contrast, surface processes accounting for these unconformable deposits in Sicily are experimentally supported. While it is not possible to simulate gravity-driven reworking of wedge materials in the experiment, erosional and depositional pulses related to uplift, emersion and critical slopes are operated. Indeed, together with the retrowedge exhumation of the ATW (t_{25} and t_{28}, Figure 11, 12b and 13), and probably its emersion associated to local erosion justifies the deposition of mélange made of resedimented Sicilide-like Alpine Tethys units into the forearc basin (Figure 15a and Figure 16a). Moreover, the subcritical state of equilibrium in the retrowedge also favours major gravity-driven mass wasting processes that might have provided a significant amount of Alpine Tethys material during short-term slope destabilization events (mass-wasting, debris flows, turbidites). This tectono-sedimentary process has been already evidenced in many subduction related orogens such as the Casanova mélange of northern Apennines and Lichi mélange in Taiwan (Page and Suppe, 1981; Malavieille et al., 2016). This scenario is supported by the Late Aquitanian-Burdigalian (21-

17 Ma) Alpine Tethys exhumation phase (Figure 16a), evidenced by thermochronological analysis on outcropping ATW remnants in the Nebrodi Mounts (Di Paolo et al., 2014 and references therein). As previously discussed (section II.3), similar enigmatic Sicilide-like units were also interpreted near the front of the present day SFTB as tectonically transported units (e.g., Bianchi et al., 1987; Bello et al., 2000; Roure et al., 1990; Catalano et al., 2013a; Lentini and Carbone, 2014 among others). Nevertheless, we shown that large-scale mass wasting and erosional reworking processes better explain the occurrence of such chaotic sediments that were deposited far from the orogenic front (> 50 km). As depicted by the model, a far travelled tectonic nappe of very weak materials made of Alpine Tethys clays is mechanically implausible, unless evoking a multi-kilometer thick propagating ATW. If true, significant burial should have been recorded in southern Sicily, which is apparently not the case (Di Paolo et al., 2014). Also, since only limited Alpine Tethys volumes are documented (Figure 2), a huge erosive phase should be evoked to remove most of the far travelled ATW during the Middle-Upper Miocene, which is not supported by geological observations and thermochronological constraints (Di Paolo et al., 2014). The nappe hypothesis also fails to explain why the Floresta calcarenites above the Peloritani block and the Licata laminites in southern Sicily do not appear as syntectonic deposits (Lentini, 2000; Grasso et al., 1997). In both cases, the end of shortening before their deposition would testify of a short-living tectonic event that is not consistent with the model evolution, while mass-wasting events and debris flows are likely processes to account for such prompt unconformities.

In northern-central Sicily (South-Ouest of the Madonie Mounts), these Sicilide-like mélanges are intercalated between the underlying Numidian cover of Burdigalian to Serravalian in ages (Broquet, 1968; Carbone et al., 1990), and the overlying Castellana Sicula Fm. (Serravalian-Early Tortonian) and Terravecchia Fm. (Late Tortonian-Lower Messinian). It thus suggests a Middle-Miocene to Early Tortonian age of reworking, consistent with the age of intercalation (Serravalian-Tortonian) of the mélange in southern Sicily (Figure 8 and Figure 16b). Coming back to the model evolution, it can be noted that this phase of Sicilide-like mélange déposition is expected when the ATW overthrusts the Panormide platform (t_{25}, Figure 11), and more specifically, when the Panormide starts underplating and uplifting the ATW (t_{31} and t_{37}, Figure 11). Indeed, the associated exhumation and erosion (Figure 12b and Figure 13) of most of the ATW explain its coeval reworking in the foredeep (Figure 15b and 15c). As shown in the experiment (Figure 14b), the burial-exhumation path of a sample within the Alpine Tethys prowedge clearly shows, after a progressive ~ 4 cm burial from t_9 to t_{29} (45-145 cm of convergence), a fast exhumation, from t_{29} to t_{36} (145-180 cm of convergence) that could be compared to the second ATW denudation phase affecting the inner prism (Figure 16b), as evidenced by thermochronological analysis from Di Paolo et al., 2014 (AFT ages ~ 11 Ma, Early Tortonian).

Finally, gravity-driven processes most probably did not only reworked Alpine Tethys sediments. Indeed, olistostromes and mélanges facies have also been described in the Upper Tortonian Terravecchia Fm. and Lower Pliocene Trubi deposits (Carbone et al., 1990; Tortorici et al., 2014), even though mud diapirism can be also evoked for some of them (e.g. “Argille brecciate”, Monaco and Tortorici, 1996). Tortonian-Early Messinian Terravecchia Fm. in the Caltanissetta area also includes varicolored clays and Numidian turbidites olistostromes (Tortorici et al., 2014), showing that such reworking events continued after the deposition of the Sicilide-like units in central-southern Sicily. It may also be noted that large-scale gravitational mass movements are still active today at the submarine front of the Gela nappe, as evidenced offshore by seismic reflection and high resolution bathymetric data (Trincardi and Argnani, 1990; Minisini et al., 2007; Cavallaro et al., 2017).

IV.2 - Panormide platform underthrusting and underplating

As discussed in the section II.2, the Panormide platform units, which are only recognized in northern Sicily (Figure 2, Figure 5a and 5c) constitutes a key tectono-stratigraphic unit initially localized at the front of the African paleomargin. Although some authors still propose that the Imerese units were overthrusted above the Panormide platform (Catalano and Di Maggio, 1996; Catalano et al., 2000; Catalano al., 2013a), field evidences in the Madonie Mounts (Figure 6a and Figure 6b) clearly show the Panormide platform units overthrusting the deep-water Imerese units (see also Barreca and Monaco, 2013 and references therein). This tectonic relationship is well reproduced by our tectonic model (Figure 15c and 15d), confirming that the initial restored section in the Figure 9 can mechanically evolves consistently with the present day structure of the Sicilian wedge.

West of the Madonie Mounts, the syntectonic Upper Burdigalian-Langhian Tavernola marls (Gugliotta et al., 2014) overlies the Imerese unit and thus dating the onset of the Panormide thrusting to Langhian (Catalano et al., 2011). Moreover, the evidences of Alpine Tethys units above the Burdigalian Castelbuono Fm. (top of the Panormide sequence) and Tavernola Fm. (top of the Imerese) also testify that the Panormide underthrusting beneath the ATW was coeval to the platform décollement.

Such mechanism is observed in the analogue model (t_{31} and t_{37}, Figure 11). The transition from shallow to deep-seated tectonics is related to the increase of normal stress induced by the uplift and thickening of the ATW, raising shear stress at greater depth consequently. The gradual rooting of the basal décollement beneath the Meso-Cenozoic foreland cover finally resulted in the underplating of the Panormide below the ATW. This underplating phase is favored by the out-of-sequence ATW nappe thrusting that prevails the burial of the platform (~ 4 cm, from t_{34} to t_{42}, Figure 14b) before its later tectonic exhumation (> t_{45}). Such scenario is in agreement with previous studies showing that the Panormide platform was tectonically buried by the Alpine Tethys accretionary wedge during the Langhian-Early Tortonian (Dewever et al., 2010; Di Paolo et al., 2014). At present day, the locally outcropping of the Panormide and Imerese stack in the Madonie Mounts is likely related to a late-stage phase of exhumation, probably during the Lower Pliocene (Barreca and Monaco, 2013) induced by a basement-involved deep thrusting phase (> t_{45}, Figure 11), as suggested by the interpretation of the SIRIPRO seismic profile (e.g., Catalano et al., 2013a). Another explanation for the lack of exhumed Panormide units in northeastern Sicily, although inferred in the near surface (Maragone 1 well, Bianchi et al., 1987), is to consider that the Panormide promontory was also thinning to the NE (Figure 3a), and thus, of limited extension in Eastern Sicily.

Finally, the present day ~ N-S thrust contact between the Panormide and Imerese in the Madonie Mounts has been analyzed through paleomagnetic campaigns (Speranza et al., 2003; 2018) and structural field works (Barreca and Monaco, 2013). It has been shown that a ~ 60-70° clockwise rotation occurred between the Imerese and the Pliocene syntectonic sediments since the Middle Miocene, but no significant rotation was recorded between the Panormide and the underlying Imerese. This lack of early rotation probably means that the onset of the orogenic wedge building was mainly controlled by orthogonal convergence and deformation partitionning (Figure 3a to 3c). The Serravalian to Messinian gradual wedge rotation (Speranza et al., 2018) corresponds to the arc engagement throughout the Tethys-Ionian corridor (Figure 3c to 3e), sandwiched between the African and Apulian plates and to concomitant bending due to indentation of the Pelagian Block (Barreca and Monaco, 2013).

IV.3 - Fold-and-Thrust Belt building steps and revised interpretation

The different SFTB building phases proposed in section II.4 are reproduced at first-order by the analogue model and discussed hereafter to improve reconstructions of the Sicilian orogeny. First, the ATW growth in the model (from t_0 to t_{18}, Figure 11) is characterized by a low taper (5-7°), in agreement with the nearby present-day tapers of the Calabrian Wedge (5-10°, Maesano et al., 2017; Doglioni et al., 2001) and Western Mediterranean Ridge (~ 3°, Chamot-Rooke et al., 2005a). A forearc basin is reproduced in our simulation above the Peloritani backstop front and gradually confined trenchward by the retrothrusting of the wedge. This retrowedge setting is common in nature as testified by the backthrusted Mediterranean Ridge and its wide forearc basin, the so-called Hellenic trench (e.g., Chaumillon and Mascle, 1997; Chamot-Rooke et al., 2005a). However, instead of being completely buried beneath the forearc basin and partly underthrusted beneath the retrowedge as in the early phases of the simulation (up to t_{31}, Figure 11), the Peloritani basement overthrusts the ATW along the Taormina Line (Figure 2, Lentini et al., 1995; Giunta and Nigro, 1999). Such backstop geometry is similar to the one found in the northern Cascadia subduction zone (e.g., Davis and Hyndman, 1989) and was assigned to an “arcward-dipping” backstop in which the deformation involves dragging of wedge material beneath the backstop (Byrne et al., 1993). Therefore, an improvement of the backstop geometry including a higher rigid backstop basal-dip (> 21°) might help to better reproduce the Peloritani-ATW contact by favoring backstop thrusting versus retrowedge backthrusting.

Then, the gradual ATW thrusting above the African margin slowed-down its frontal growth (Figure 14a), enhancing internal shortening and thickening. This tectonic setting is typical of high-friction zones underthrusted beneath a low-tapered wedge (Larroque et al., 1994). A relevant present day analogue situation is also found in the central Mediterranean Ridge (e.g., Chaumillon and Mascle, 1997), where the incipient overthrusting of the Libyan margin locally shortened the wedge up to ~ 70% compare to its length in the Western counterpart. During that phase, major backthrusting in the retrowedge induces steep slopes prone to gravitational instabilities as evidenced by previous experimental models (Malavieille et al., 2016). This phase corresponds to the emplacement of the "Antisicilide" unit in the forearc basins of the Peloritani and Calabrian backstops as discussed in section IV.1 and illustrated by the cartoon from Figure 16a. According to the previous remarks concerning the Late Burdigalian Antisicilide unit, and the Lower Miocene Sicilide antiformal stack (Di Paolo et al., 2014), readjustment of the accretionary wedge occurred long before the post-Langhian (Butler et al., 2019) overthrusting of the Panormide promontory. Thus, while the accretionary wedge probably reached the Panormide platform of the African margin during the Middle Miocene, its encounter with a wide ocean-continent transition zone characterized by a thinned continental crust was already effective since the Early Miocene (Figure 9b). To that extent, it is likely that early thrusting of Sicilide nappes over the internal portion of the thinned African margin was coeval with the Numidian Flysch deposition as suggested by the "confined" model (Pinter et al., 2016 and 2018). The "far travelled" Numidian Flysch of the inner wedge could then be considered as synkinematic sediments in thrust-top and foredeep depocenters (Butler et al., 2019).

The following phase is represented by the ATW overthrusting the Panormide platform and its progressive detachment, initiating thick-skinned foreland tectonics (section IV.2). During the Middle Miocene, this stage was also occurring in the northward Apennines belt (Vitale and Ciarcia, 2013 and references therein). Indeed, the Campania-Lucania platform (Panormide equivalent) was underthrusted, from the Uppermost Burdigalian, beneath the Ligurian Accretionary Complex (ATW equivalent), and then progressively overthrusted, since the Serravalian, above the Lagonegro–Molise Basin (Imerese-Sicanian equivalent).

To summarize, this modeling approach; 1) validates the first-order African and Apulian margins paleogeographic structure and 2), supports the gravitational and erosional reworking of Alpine Tethys units from the ATW and their deposition into syntectonic foreland and forearc basins. Consequently, since the Middle Miocene, the front of the oceanic accretionary wedge likely dissociated from the orogenic deformation front (Figure 14a) and remained in a backward position up to present day (Figure 17b and 17c).

The deformation then propagated to the Imerese-Sicanian basin where frontal accretion was the dominant wedge growing process. However, unlike the model outcomes suggest (t_{53}, Figure 11, and t_{51}, Figure 17a), only a few basinal units outcrop in Central-Eastern Sicily (Figure 2). This situation also diverges from the analogous southern Apennines case where the Lagonegro-Molise basinal units widely outcrop (e.g., Vitale and Ciarcia, 2013). One explanation could be that the late orogenic uplift, mainly enhanced by deep-seated basement thrusting and isostatic rebound related to slab-detachment, is slightly more advanced in the southern Apennines (e.g., Speranza and Chiappani, 2002; Vitale and Ciarcia, 2013) than in Sicily (e.g., Bello et al., 2000; Guarnieri et al., 2002; Finetti, 2005; Catalano et al., 2013a).

One could note that the basinal units in the model are widely exhumed all over the wedge at the end of the experiment (t_{53}, Figure 11). One reason is that in the model, the tectonic shortening and associated uplift (Figure 12b and Figure 13) might be slightly too high compared to the simulated sedimentation rate after t_{44} (Figure 15d). As shown by analogue modeling, syntectonic sediment supply tends to increase the thrusts spacing favoring, then, fast wedge lengthening (e.g., Storti and McClay, 1995). Consequently, the low sediment ation rate together with a potentially excessive basal décollement strength explain why the model reached a relatively high taper, > 15°, compared to nature, 10-12° (Bello et al., 2000; Catalano et al., 2013a). Such syntectonic sedimentation from the Upper Miocene is actually preserved in central-southern Sicily (e.g. the Caltanissetta basin; Figure 6e) where Late

Tortonian to Pliocene terrigenous deposits can locally reach a thickness of 1000 to 2000 m (e.g., Bello et al., 2000).

The Late Messinian-Pliocene phase is marked in Central-Eastern Sicily by two diverging but compatible scenario. On one side, to the West, basement-involved deep-seated thrusting led to the exhumation of the Madonie Mounts (Figure 17c) and to the south of Caltanissetta, to the formation of the confined Caltanissetta basin and its internal deformation (Figure 6e) referred as the Gela Thrust System (Catalano et al., 2013a; Gasparo Morticelli et al., 2015). Out-of-sequence thrusting also occurred at that time as testified by Early Pliocene sediments pinched by thrusting of the Panormide and Imerese units in the Madonie mountains (Abate et al., 1993; Catalano et al., 2011). On the other side, to the East, the encounter of the orogenic front with the anomalous Hyblean platform high (Henriquet et al., 2019 and references therein) induced a localized stacking and subsequent exhumation of the Judica basinal units thermochronologically dated to the Messinian-Late Pliocene (Di Paolo et al., 2012; 2014). Indeed, the underthrusted Hyblean promontory acted like an indenter and led to a steepening of the basal detachment that forced the frontal stacking of these thin basinal units (Figure 15e and Figure 11). Furthermore, the frontal position of this thrust-stack, ~ 10 km back of the present day deformation front (Figure 2 and Figure 5), and the tectonic evolution of the model are compatible with a late Judica thrust-stack detachment from its substratum. We rather favour a short travel distance of the Judica units (< 10-20 km) rather than ~ 200 km (Figure 5b) claimed by Butler et al. (2019).

V - Conclusion

The objective of this study was review the Sicilian Fold-and-Thrust Belt (SFTB) evolution since Oligocene roll-back initiation and to propose an updated tectono-stratigraphic dynamic model. To do so, we performed a critical review of the literature, poiting out the well constrained evidences and the remaining controversies such as; 1) the occurrence of widely different tectonic scenarios arising from divergent structural interpretations (e.g., Bianchi et al., 1987; Roure et al., 1990; Bello et al., 2000; Catalano et al., 2013a; Butler et al., 2019), 2) the occurrence of oceanic Alpine Tethys units far from the region where the remnants of the Alpine Tethys Wedge (ATW) outcrop (Nebrodi Mountains), both in a forearc position on the Peloritani block and in an active foreland context along the southern front of the SFTB; and 3) the paleogeography and global tectono-stratigraphic evolution of the SFTB

To test the mechanical consistency of the most probable evolutionary scenario, we used a challenging experimental approach attempting to simulate the main construction phases of the SFTB. The analog model succeeds in reproducing the general structure of the SFTB and associated main tectono-stratigraphic relationships. First, the model revealed that the first order reconstructed African margin architecture (Figure 9) is compatible with the main stacked tectonic units that are identified in central-eastern Sicily. Indeed, the inferred paleogeographic setting successfully evolved toward a final model state consistent with the present day structure of the SFTB. The second major model outcome concerns the anomalous position of inferred Alpine Tethys units within the forearc and foreland sequences. The model effectively supports gravity-driven and erosional processes at the origin of these Sicilide-like mélanges intercalated in the syntectonic sedimentation (Figure 16). It is likely that since its encounter with the African margin, the ATW never reached the present day deformation front but gradually retreated compared to the orogenic front, in response to out-of-sequence thrusting activity and exhumation.

Based on the literature review, experimental results and additional fieldwork investigations, we propose an updated synthetic geological cross-section across the central-eastern SFTB (Figure 17b and 17c) integrating the distinction between the Sicilide units from the ATW from those reworked by gravity-driven and erosional processes. We propose also the following tectonic evolution. During the first stages of slab rollback, from the Middle Oligocene to the Lower Miocene, frontal accretion of weak oceanic sediments at the front of the drifting Corso-Sardinia block (CSB) induced the formation of a low-tapered Alpine Tethys Wedge (ATW). Backthrusting on the retrowedge localized a passive forearc basin developing mainly above the eastern termination of the CSB, i.e; the future Peloritani and Calabria blocks. The progressive underthrusting of the stretched African continental margin beneath the ATW, induced then, significant internal shortening and thickening providing gravitational instabilities along the retrowedge at the origin of the Late Burdigalian "Antisicilide" deposition into the forearc basin. While the Tyrrhenian back-arc initiated its opening during the Middle Miocene, the Panormide platform gradually underthrusted beneath the ATW, then started to detach from its ante-Triassic basement. During the Serravalian-Early Tortonian, along with the ongoing out-of-sequence thrusting of the ATW, deep-seated thrusting and platform underplating might have contributed to prowedge gravitational instabilities and the coeval deposition of Sicilide-like mélanges inside the foreland successions. This deep-seated tectonic setting progressively led to a second phase of wedge growth by frontal accretion of Meso-Cenozoic basinal units (Imerese-Sicanian basin) covered by the reworked Alpine Tethys materials. Finally, from the Messinian, thick-skinned deformation involving the ante-Mesozoic basement initiated the general uplift and exhumation of the wedge while the Hyblean platform indenter locally forced the exhumation of the Judica thrust-stack at the orogenic front. Therefore, our model is not compatible with the large-scale nappe thrusting hypothesis commonly inferred by tectonic interpretations and reconstructions of the SFTB.

Finally, this study not only gives insights on key processes concerning the Sicilian Fold-and Thrust Belt evolution, it also provides tectonic mechanism applicable to analogue subduction related orogens such as the nearby Apenninic belt that followed a similar geodynamic evolution.

Acknowledgements

This study was funded by the "DEF-eSICILY" project (TelluS-ALEAS and TelluS-SYSTER INSU-CNRS 2018 and 2019 programs) and also benefited from Catania University funds in the frame of the project "multidisciplinary analysis of the deformation around active tectonic structures" (Resp. G. Barreca). Many thanks to C. Romano for technical support and help with analogue modeling. The free GMT software (Wessel and Smith, 1991) has been widely used for illustrations and data processing. Data used in this study are available in the figures and appendices. We also wish to thanks the three anonymous reviewers for their constructive comments that significantly improved the manuscript.

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Figures caption

Figure 1: General geodynamic and tectonic map of Central Mediterranean. Geological data are synthetized from large-scale maps (Funiciello et al., 1981; Bigi et al., 1991; APAT, 2005; Lentini and Carbone, 2014), and local maps for the Tunisian region (Bouhlel et al., 2007; Melki et al., 2012; Zouaghi et al., 2013). Structural data are synthetized and harmonized from previous publications (e.g., Finetti, 2005; Chamo-Rooke et al., 2005b; Corti et al., 2006; Prada et al., 2014; Lymer et al., 2018; Rabaute and Chamot-Rooke, 2019). Green stars outline ophiolites from the Alpine orogenic cycle (Funiciello et al., 1981). Present day seismic moment tensors (Mw > 4.5) and kinematic GPS data are from https://www.globalcmt.org/CMTsearch.html and https://www.unavco.org/data/gps-gnss/gps-gnss.html websites, respectively.

Figure 2: Onshore geological map of central-eastern Sicily and offshore neotectonic map. Simplified geological data (mostly after Lentini and Carbone, 2014) representing the main tectono-stratigraphic units of Sicily, except for the post-Middle Miocene sediments that are age-ranked. Shaded-relief background comes from the compilation of bathymetric data from Gutscher et al. (2017) and topographic data from the Japan Aerospace Exploration Agency (https://www.eorc.jaxa.jp). Offshore tectonics is interpreted from the bathymetry and previous works (e.g., Bortoluzzi et al., 2010; Cultrera et al., 2017; Gutscher et al., 2017). Note that the deep purple unit referred as Burdigalian to Tortonian varicolored clays mélange and Numidian Flyschs described as “far-travelled” units in Lentini et al. (2014) corresponds to our interpretation (discussed in the text).

Figure 3: Paleogeographic cartoons showing the Neogene-Quaternary evolution of the Maghrebian-Sicilian-Apennines orogenic belt. Large-scale reconstructions are mainly based on previous compilations (Carminati et al., 2012; Cifelli et al., 2007; Barreca and Monaco, 2013; Vitale and Ciarcia, 2013; Faccenna et al., 2004, 2014; Van Hinsbergen et al., 2020). Initial positions (a) of the Corso-Sarde block and the Adriatic plate relative to Africa come from Le Breton et al. (2017). The North African margin involved in the Sicilian belt is a simplification of the paleogeographic models from Oldow et al. (1990) and Catalano et al. (1996). Global kinematics (black arrows) is extrapolated from the relative motion of the main paleogeographic domains between each illustrated steps. The yellow curve represents the evolution of the general cross-section discussed in this study.

Figure 4: Simplified Sicilian lithostratigraphic columns and main tectonic relationships. The synthesis (mostly after Roure et al., 1990; Lentini et al., 1995; Giunta and Nigro, 1999; Finetti et al., 2005; Lentini and Carbone, 2014, Basilone, 2009, 2011, 2018 and references therein) describes the main Sicilian tectono-stratigraphic units: the European remnant (A, Peloritani), the Alpine Tethys relicts (B), the accreted African margin cover (C, Panormide platform, D and E, Imerese-Sicanian basin), the African foreland units (F and G, Trapanese and Hyblean platform), and the post-Lower Miocene wedge-top syntectonic deposits (H). The detailed stratigraphy of each column is given in Appendix A.

Figure 5: Review of published geological cross-section across central-eastern Sicily, redrawn and standardized to highlight the main differences in the interpretation of the SFTB tectono-stratigraphy (a, Bianchi et al., 1987; b, Roure et al., 1990; c, Butler et al., 2019; d, Bello et al., 2000; e, Catalano et al., 2013a). Note that in addition to surface geology, cross-sections a, d

and e are interpretated from seismic surveys and locally constrained by wells data (up to ~ 5 km depth). Differences mainly concern the tectonic structures inferred at depth, the associated shortening amount and the interpretation of Sicilide units at the wedge front.

Figure 6: Panoramic views and outcrops of major tectonic structures of the SFTB. a) Thrusting of the Panormide platform above the Imerese basin and late stage exhumation of the Madonie Mountains, highlighted by the Mt. Dei Cervi ramp anticline and the frontal Scillato-Petralia Thrust (SPT). In the background, inferred Alpine Tethys units are intercalated between the Imerese Numidian cover (NF_{PC} and NF_{GS}) and the Early Tortonian Geraci Siculo syntectonic deposits (GS). b) Tectonic contact between the Upper Triassic Mufara Fm. at the base of the Panormide platform and the underthrusted Upper Oligocene-Lower Miocene Portella Colla member belonging to the basal Numidian cover of the Imerese basinal unit (location: yellow star in figure a, lon/lat: 14.016°E/37.872°N). c-d) Outcrops of the highly deformed (folded and sheared) Upper Triassic Mufara Fm. from the base of the platform at the Panormide-Imerese thrust-contact (location: yellow star in figure a, lon/lat: 14.017°E/37.867°N). e) Panoramic view showing the Imera syncline and Mt. Grande fold (SE of Caltanissetta). Syntectonic sedimentation occurred in the tectonically shortening Caltanissetta basin, at least since the Upper Tortonian (Terravecchia sedimentation) and after the Pliocene.

Figure 7: Examples of inferred Alpine Tethys units outcrops from the inner wedge (in the present day Nebrodi mountains), and within the forearc sedimentation (Peloritani mountains). a) Typical varicolored clays of the Troina subunit showing a diffuse/plastic deformation of reddish-greenish Oligocene-Early Miocene clays (SE of Troina, lon/lat: 37.738°E/14.687°N). b) Chaotic varicolored clays with fragments of carbonatic siltites and Numidian quartzarenites (E of Campogrande, lon/lat: 15.106°E/38.075°N). c and d) Chaotic varicolored clays with scarce soft-sediment folds and fragments of micritic siltites and Numidian quartzarenites (NE of Patti, lon/lat: 14.974°E/38.144°N). Outcrops b, c and d (“Antisicilide” Fm.) might represent gravity flow deposits reworking varicolored clays from the retro-wedge (Upper Cretaceous faunas) and other younger lithologies such as Numidian sandstones.

Figure 8: Outcrops of inferred Alpine Tethys units in central and southern Sicily. a) Chaotic Alpine Tethys units at the southern front of the Madonie Mounts (S of Polizzi, lon/lat: 13.991°E/37.769°N). b) Zoom (black box located in Figure a) on the block-in-matrix facies of the quartzitic turbidites above chaotic varicolored clays including clasts of Numidian Flysch, clays and jasper. c) Chaotic reddish-greenish clays including clasts of Numidian Flysch, clays and jasper (outcrop 100 m to the south of Figure a and b). d) Simplified stratigraphic column from the offshore Leone 001 well, with recognized varicolored clays intercalated in the lower part (lon/lat: 13.540°E/37.205°N). e) Potentially resedimented brownish-grayish Sicilide-like sediments, locally overthrusting the overlying Licata laminites (N of Licata, lon/lat: 13.922°E/37.767°N). f) Zoom on the chaotic brownish-grayish clays.

Figure 9: First-order restored and simplified lithospheric cross-sections representing the paleogeodynamic setting retained for the analogue model initial states. These sections are based on the paleogeographic reconstruction (along the yellow lines in Figure 3). a) Early Alpine Tethys subduction phase (Oligocene). b) Onset of the frontal African margin continental subduction (~ Middle Miocene). Each cross-section is represented with (up) and without (down) vertical exaggeration (x 4).

Figure 10: Set-up and boundary conditions of the experimental sandbox apparatus used for modeling the SFTB. Geometries and rheological stratification are based on the reconstructed cross-section presented in Figure 9 and the stratigraphic synthesis of Figure 4. Analogue materials representing the Alpine Tethys and African margin sedimentary cover are pulled against the Peloritani-like backstop. Note the initial set-up is at 1:1 scale but laterally shortened by six cuts.

Figure 11: Main steps (11) of the SFTB analogue model evolution (corresponding video in the Appendix B). Each step is presented with a picture (a) and the corresponding stratigraphic and structural interpretation (b). Thick and thin black lines represent major and minor active faults while dashed lines underline incipient faults. The white cross-arrows indicate compressional diffuse deformation. Syntectonic sedimentation and equivalent formation names in nature are indicated. The Alpine Tethys wedge front (ATF) and the deformation front (DF) are indicated by red and black arrows (b). Locations of the samples selected to construct burial-exhumation paths (see Figure 14b) are shown in blue at t_{31} and t_{44} (b).

Figure 12: Quantitative measurements of the deformation and model kinematics of the 10 steps presented in Figure 11 (t_0 excluded). Incremental shear strain (a) and vertical displacement field (b), calculated for each 2.5 mm of shortening between 2 pictures. “R_{ExC} equivalent” is the incremental ratio of the vertical displacement field relative to the 2.5 mm of shortening. The cumulated subsidence (mm) and the ratio between the material output and shortening (R_{OuC}) are also indicated (b).

Figure 13: Erosion (red) and sedimentation (green) profiles performed manually across the modeled wedge for the 10 steps presented in Figure 11 (t_0 excluded). The equivalent ratios between erosion/sedimentation and shortening (R_{ErC} / R_{SeC}) are given on the right. Main active faults (black) and uplifted zones (red arrows) are indicated above the model topography. These profiles are extracted by calculating the difference between topographic profiles extracted before and after the corresponding erosion/sedimentation phase.

Figure 14: Deformation front motion and burial-exhumation paths along the model evolution. a) Locations of the Alpine Tethys wedge Front (ATF, purple) and orogenic Deformation Front (DF, black) relative to the initial position of the first modeled frontal thrust. ‘x-axis position’, corresponds to the lateral position of the ATF and DF relative to the ‘First thrust front’, located in Figure 11a (t_0) with positive values to the right of the initial position (wedge growth). The dashed purple line represents the retreating front of the ATW in response to its exhumation and erosion. Wedge encounter with the 3 margin front steps (step 1 and 2 are the rigid blocks, step 3 is the Panormide-like platform) and major thrusting (red) and back-thrusting (dashed red) events are indicated. b) Burying thicknesses of relevant samples taken in the simulated ATW (sample 1) and the African margin cover (2 to 5). Sample locations are shown in Figure 11a (t_{31} and t_{44}). Sample 3 correspond to the top of the Panormide-like platform. Sample 2 and 4 are taken in the resedimented AT mélange above the Panormide-like platform and the Imerese-like basin respectively. Sample 5 is taken from the sedimentary cover of the Sicanian-like unit juxtaposed to the Hyblean promontory.

Figure 15: Selection of model key features used to discuss tectonic and surface processes considered as primary mechanisms explaining the SFTB tectono-stratigraphic evolution. a) Retrowedge exhumation and gravity-driven reworking of wedge materials in the forearc basin. b-c) Frontal exhumation of the ATW and gravity-driven reworking of wedge materials in the foredeep along with the progressive underplating of the Panormide platform beneath

the ATW. d) Wedge growth by frontal accretion of the Imerese-Sicanian basinal units. e) Frontal thrust-stack of the thinned Sicanian basinal units together with the indentation of the thick Hyblean platform. Thick and thin black lines represent the active or inactive faults and red arrows indicate the uplifted portions of the wedge. Dashed blue, red and black lines correspond to the bottom of the analogue Numidian cover, the base and top of the resedimented Sicilide-like mélange and the base of Messinian-Pliocene syntectonic sediments respectively.

Figure 16: 3D block diagrams (inspired and substantially modified after Cavazza and Barone, 2010) illustrating the emplacement mechanism of the "Antisicilide" Fm. in the forearc basin (a), and of the "far travelled Sicilide" units in the foreland succession (b). Remobilization of Alpine Tethys units from the wedge signs subcritical state of equilibrium due to the collision of the ATW with the African margin. From the wedge to distal depocenters, large-scale mass-wasting, debris flows and turbiditic channelized systems favors a major remobilization of Alpine Tethys units.

Figure 17: Final model outcomes and updated cross-sections of the central-eastern SFTB. a) Stratigraphic and structural interpretation of the model at step 51 with a fictive post-orogenic erosion and sedimentation. b) Reinterpreted cross-section from the Tyrrhenian coastline to the Hyblean Plateau across the Nebrodi Mountains and the Judica thrust-stack. c) Equivalent cross-section focused on the Madonie Mountains further West. The suspected Sicilide-like mélange are distinguished from the Alpine Tethys units although the position of the present day Alpine Tethys Front (ATF) remains speculative. Note that the exhumed Panormide units in the Madonie Mountains might be correlated to a more advanced deep-seated thrusting of the African basement.

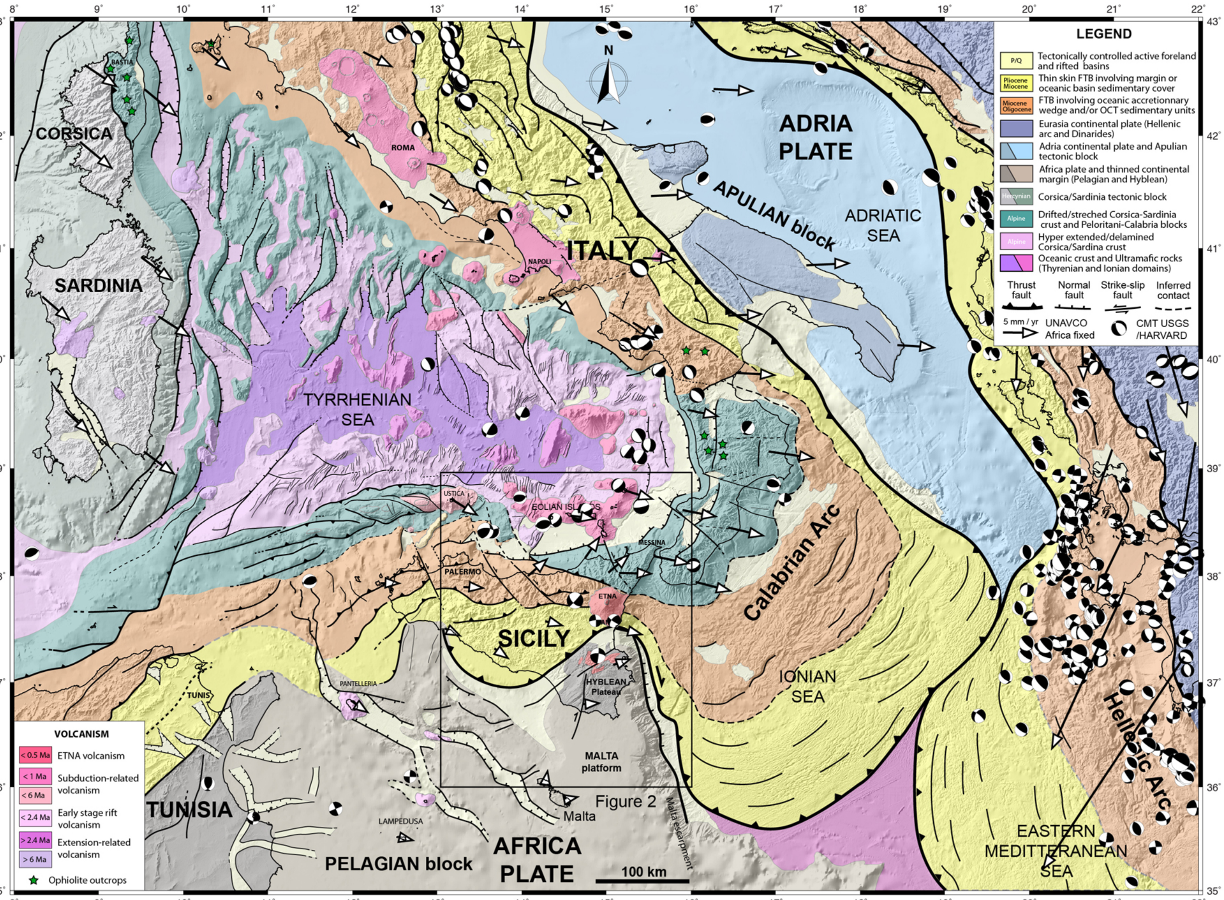

LEGEND
Tectonically controlled active foreland and rifted basins
Thin skin FTB involving margin or oceanic basin sedimentary cover
FTB involving oceanic accretionnary wedge and/or OCT sedimentary units
Eurasia continental plate (Hellenic arc and Dinarides)
Adria continental plate and Apulian tectonic block
Africa plate and thinned continental margin (Pelagian and Hyblean)
Corsica/Sardinia tectonic block
Drifted/streched Corsica-Sardinia crust and Peloritani-Calabria blocks
Hyper extended/delamined Corsica/Sardina crust
Oceanic crust and Ultramafic rocks (Thyrenian and Ionian domains)
Thrust fault
Normal fault
Strike-slip fault
Inferred contact
5 mm / yr
UNAVCO Africa fixed
CMT USGS /HARVARD
VOLCANISM
ETNA volcanism
Subduction-related volcanism
Early stage rift volcanism
Extension-related volcanism
Ophiolite outcrops
CORSICA
SARDINIA
TYRRHENIAN SEA
ROMA
NAPOLI
ITALY
ADRIA PLATE
APULIAN block
ADRIATIC SEA
Calabrian Arc
IONIAN SEA
SICILY
PALERMO
ETNA
HYBLEAN Plateau
MALTA platform
Malta
Figure 2
TUNISIA
PELAGIAN block
AFRICA PLATE
LAMPEDUSA
PANTELLERIA
100 km
EASTERN MEDITTERANEAN SEA
Hellenic Arc

Figure 1

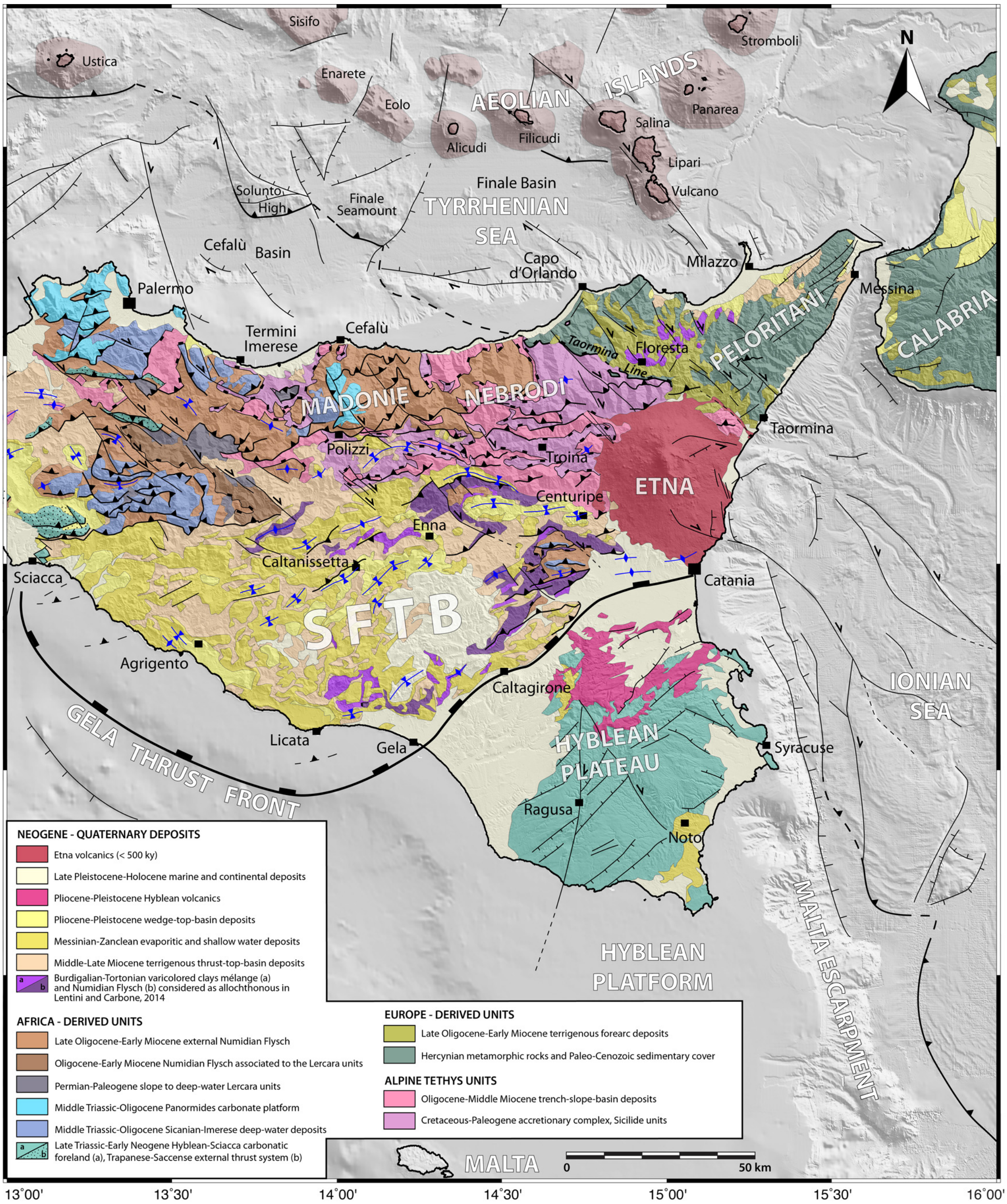

NEOGENE - QUATERNARY DEPOSITS
Etna volcanics (< 500 ky)
Late Pleistocene-Holocene marine and continental deposits
Pliocene-Pleistocene Hyblean volcanics
Pliocene-Pleistocene wedge-top-basin deposits
Messinian-Zanclean evaporitic and shallow water deposits
Middle-Late Miocene terrigenous thrust-top-basin deposits
Burdigalian-Tortonian varicolored clays mélange (a) and Numidian Flysch (b) considered as allochthonous in Lentini and Carbone, 2014
AFRICA - DERIVED UNITS
Late Oligocene-Early Miocene external Numidian Flysch
Oligocene-Early Miocene Numidian Flysch associated to the Lercara units
Permian-Paleogene slope to deep-water Lercara units
Middle Triassic-Oligocene Panormides carbonate platform
Middle Triassic-Oligocene Sicanian-Imerese deep-water deposits
Late Triassic-Early Neogene Hyblean-Sciacca carbonatic foreland (a), Trapanese-Saccense external thrust system (b)
EUROPE - DERIVED UNITS
Late Oligocene-Early Miocene terrigenous forearc deposits
Hercynian metamorphic rocks and Paleo-Cenozoic sedimentary cover
ALPINE TETHYS UNITS
Oligocene-Middle Miocene trench-slope-basin deposits
Cretaceous-Paleogene accretionary complex, Sicilide units
N
Sisifo
Ustica
Enarete
Eolo
Alicudi
Filicudi
AEOLIAN
ISLANDS
Stromboli
Panarea
Salina
Lipari
Vulcano
Finale Basin
Solunto High
Finale Seamount
TYRRHENIAN SEA
Cefalù Basin
Capo d'Orlando
Milazzo
Messina
Palermo
Termini Imerese
Cefalù
Taormina Line
Floresta
PELORITANI
CALABRIA
MADONIE
NEBRODI
Taormina
Polizzi
Troina
ETNA
Centuripe
Enna
Caltanissetta
Catania
Sciacca
SFTB
Agrigento
Caltagirone
IONIAN SEA
GELA THRUST FRONT
Licata
Gela
HYBLEAN PLATEAU
Syracuse
Ragusa
Noto
MALTA ESCARPMENT
HYBLEAN PLATFORM
MALTA
0
50 km
38°30'
38°00'
37°30'
37°00'
36°30'
36°00'
13°00'
13°30'
14°00'
14°30'
15°00'
15°30'
16°00'

Figure 2

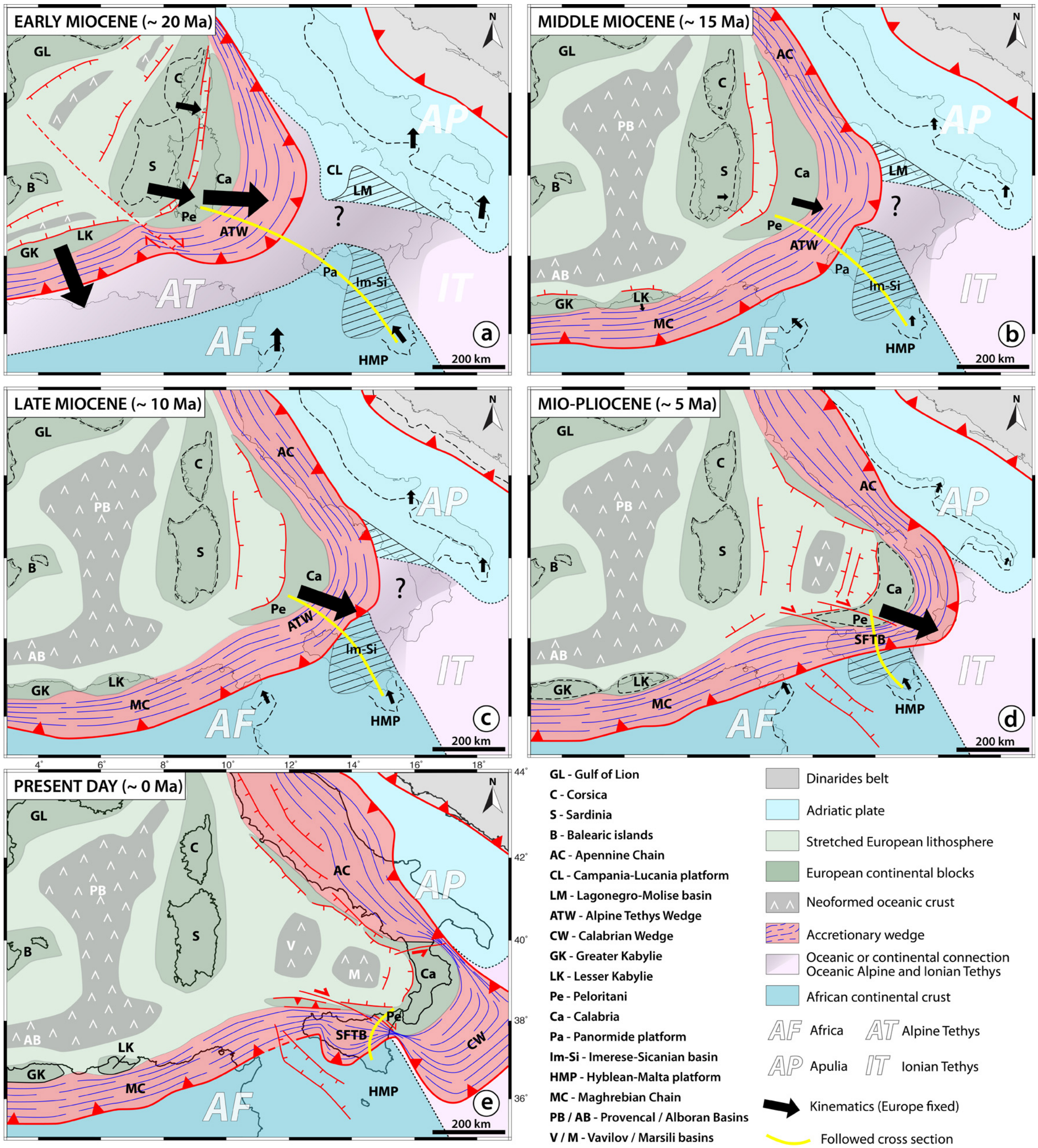

EARLY MIOCENE (~ 20 Ma)
MIDDLE MIOCENE (~ 15 Ma)
LATE MIOCENE (~ 10 Ma)
MIO-PLIOCENE (~ 5 Ma)
PRESENT DAY (~ 0 Ma)
GL - Gulf of Lion
C - Corsica
S - Sardinia
B - Balearic islands
AC - Apennine Chain
CL - Campania-Lucania platform
LM - Lagonegro-Molise basin
ATW - Alpine Tethys Wedge
CW - Calabrian Wedge
GK - Greater Kabylie
LK - Lesser Kabylie
Pe - Peloritani
Ca - Calabria
Pa - Panormide platform
Im-Si - Imerese-Sicanian basin
HMP - Hyblean-Malta platform
MC - Maghrebian Chain
PB / AB - Provencal / Alboran Basins
V / M - Vavilov / Marsili basins
Dinarides belt
Adriatic plate
Stretched European lithosphere
European continental blocks
Neoformed oceanic crust
Accretionary wedge
Oceanic or continental connection
Oceanic Alpine and Ionian Tethys
African continental crust
AF Africa
AT Alpine Tethys
AP Apulia
IT Ionian Tethys
Kinematics (Europe fixed)
Followed cross section
200 km

Figure 3

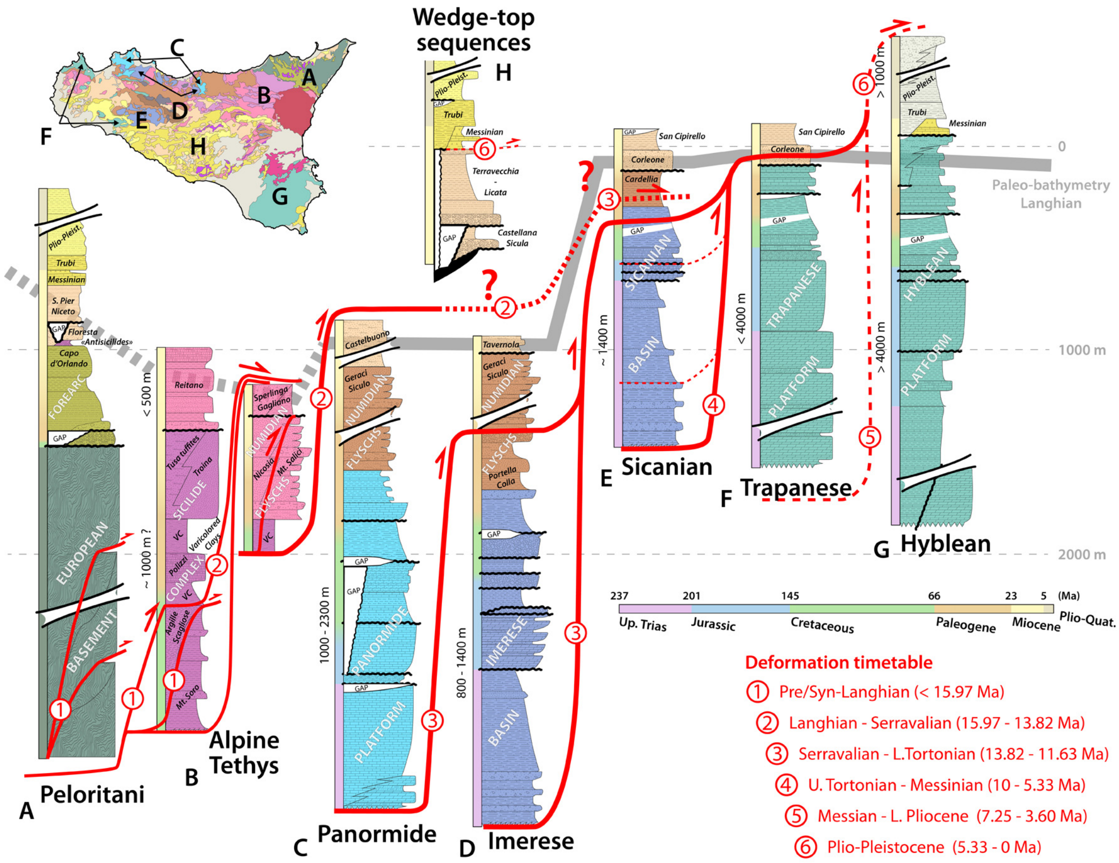
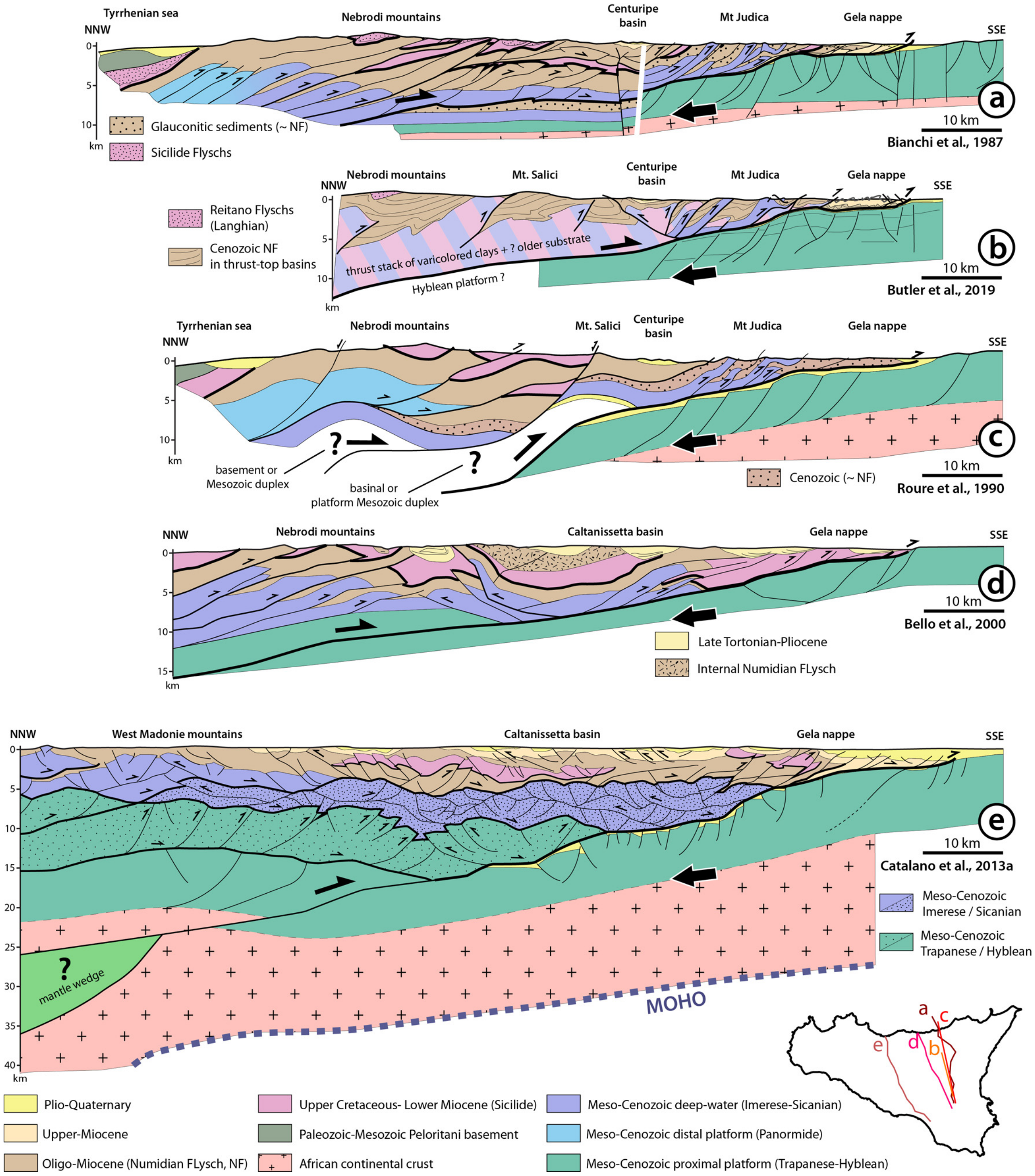

Wedge-top sequences
Peloritani
Alpine Tethys
Panormide
Imerese
Sicanian
Trapanese
Hyblean
Paleo-bathymetry Langhian
Deformation timetable
1 Pre/Syn-Langhian (< 15.97 Ma)
2 Langhian - Serravalian (15.97 - 13.82 Ma)
3 Serravalian - L.Tortonian (13.82 - 11.63 Ma)
4 U. Tortonian - Messinian (10 - 5.33 Ma)
5 Messian - L. Pliocene (7.25 - 3.60 Ma)
6 Plio-Pleistocene (5.33 - 0 Ma)
Up. Trias
Jurassic
Cretaceous
Paleogene
Miocene
Plio-Quat.

Figure 4



Tyrrhenian sea
NNW
Nebrodi mountains
Centuripe basin
Mt Judica
Gela nappe
SSE
Glauconitic sediments (~ NF)
Sicilide Flyschs
10 km
Bianchi et al., 1987
Nebrodi mountains
Mt. Salici
Reitano Flyschs (Langhian)
Cenozoic NF in thrust-top basins
thrust stack of varicolored clays + ? older substrate
Hyblean platform ?
Butler et al., 2019
basement or Mesozoic duplex
basinal or platform Mesozoic duplex
Cenozoic (~ NF)
Roure et al., 1990
Caltanissetta basin
Late Tortonian-Pliocene
Internal Numidian FLysch
Bello et al., 2000
West Madonie mountains
Catalano et al., 2013a
Meso-Cenozoic Imerese / Sicanian
Meso-Cenozoic Trapanese / Hyblean
mantle wedge
MOHO
Plio-Quaternary
Upper-Miocene
Oligo-Miocene (Numidian FLysch, NF)
Upper Cretaceous- Lower Miocene (Sicilide)
Paleozoic-Mesozoic Peloritani basement
African continental crust
Meso-Cenozoic deep-water (Imerese-Sicanian)
Meso-Cenozoic distal platform (Panormide)
Meso-Cenozoic proximal platform (Trapanese-Hyblean)

Figure 5

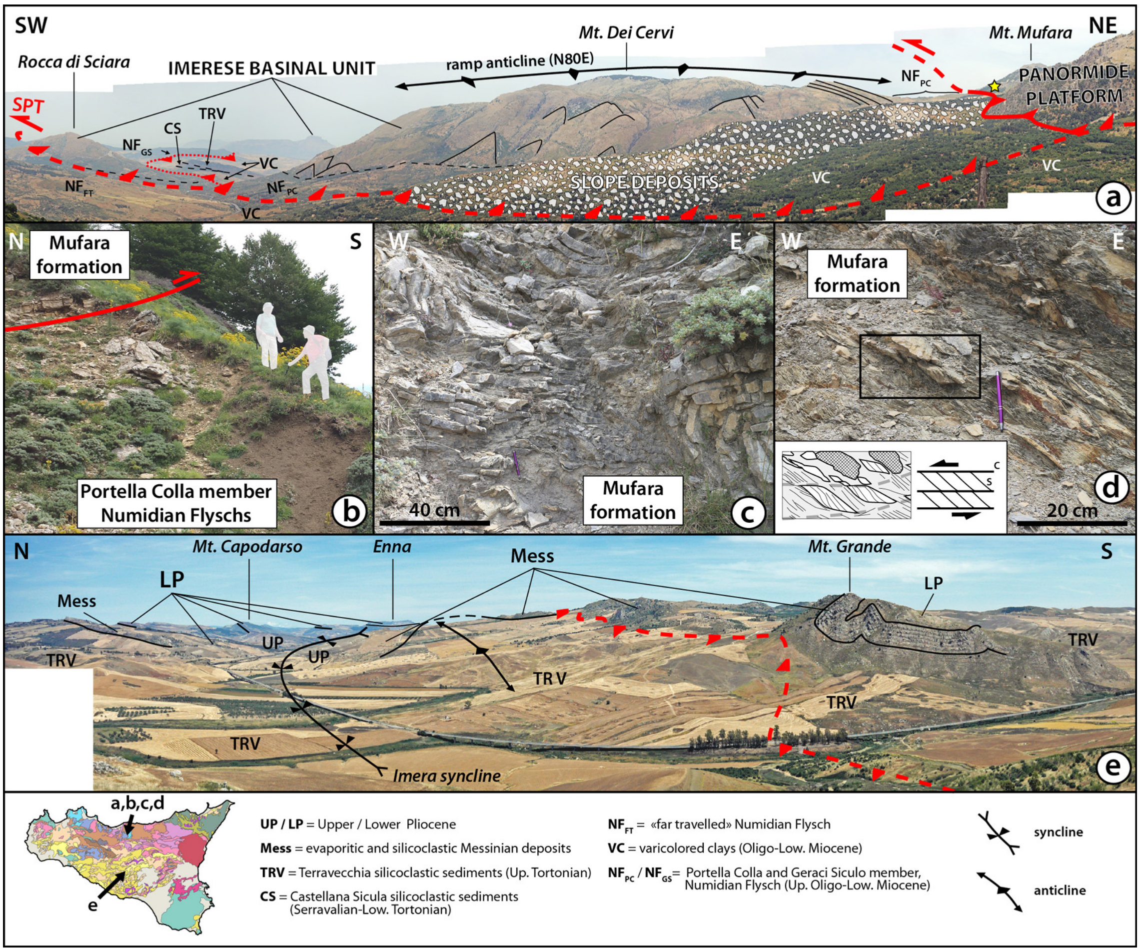

SW
NE
Rocca di Sciara
IMERESE BASINAL UNIT
Mt. Dei Cervi
ramp anticline (N80E)
Mt. Mufara
PANORMIDE PLATFORM
SPT
SLOPE DEPOSITS
VC
a
Mufara formation
Portella Colla member Numidian Flyschs
b
40 cm
c
20 cm
d
N
S
Mt. Capodarso
Enna
Mess
Mt. Grande
LP
UP
TRV
Imera syncline
e
a,b,c,d
UP / LP = Upper / Lower Pliocene
Mess = evaporitic and silicoclastic Messinian deposits
TRV = Terravecchia silicoclastic sediments (Up. Tortonian)
CS = Castellana Sicula silicoclastic sediments (Serravalian-Low. Tortonian)
NF_{FT} = «far travelled» Numidian Flysch
VC = varicolored clays (Oligo-Low. Miocene)
NF_{PC} / NF_{GS} = Portella Colla and Geraci Siculo member, Numidian Flysch (Up. Oligo-Low. Miocene)
syncline
anticline

Figure 6

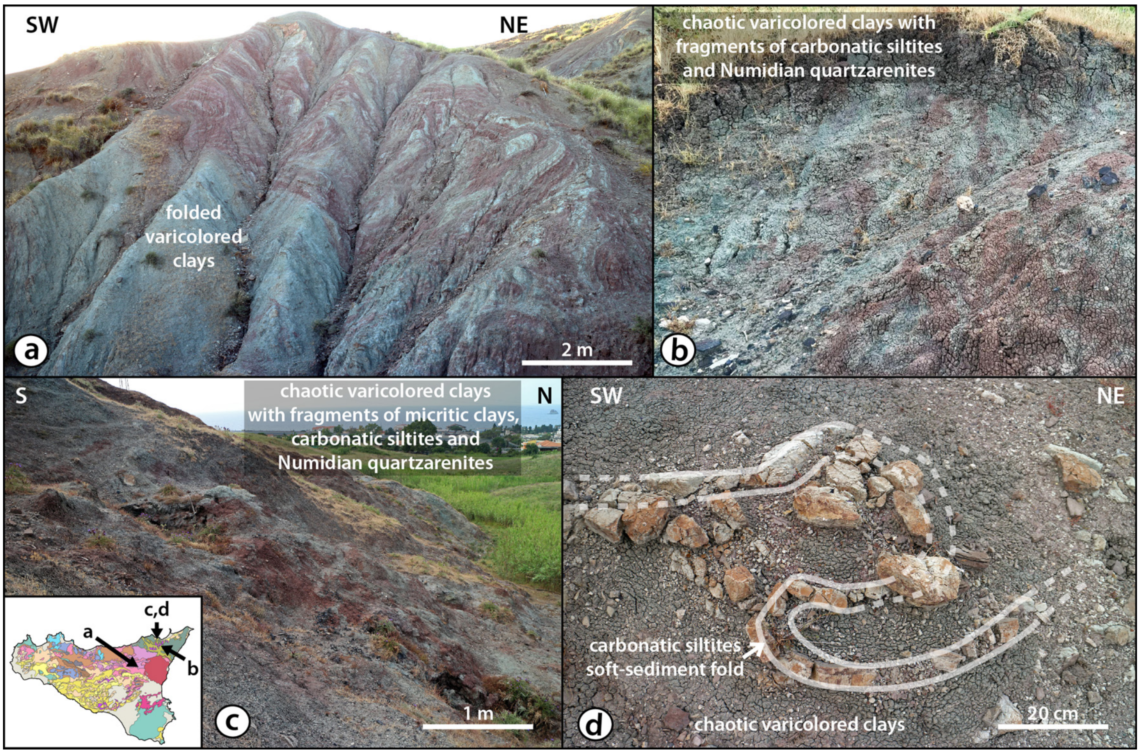

SW
NE
folded varicolored clays
2 m
a
chaotic varicolored clays with fragments of carbonatic siltites and Numidian quartzarenites
b
S
N
chaotic varicolored clays with fragments of micritic clays, carbonatic siltites and Numidian quartzarenites
c,d
a
b
1 m
c
SW
NE
carbonatic siltites soft-sediment fold
chaotic varicolored clays
20 cm
d

Figure 7

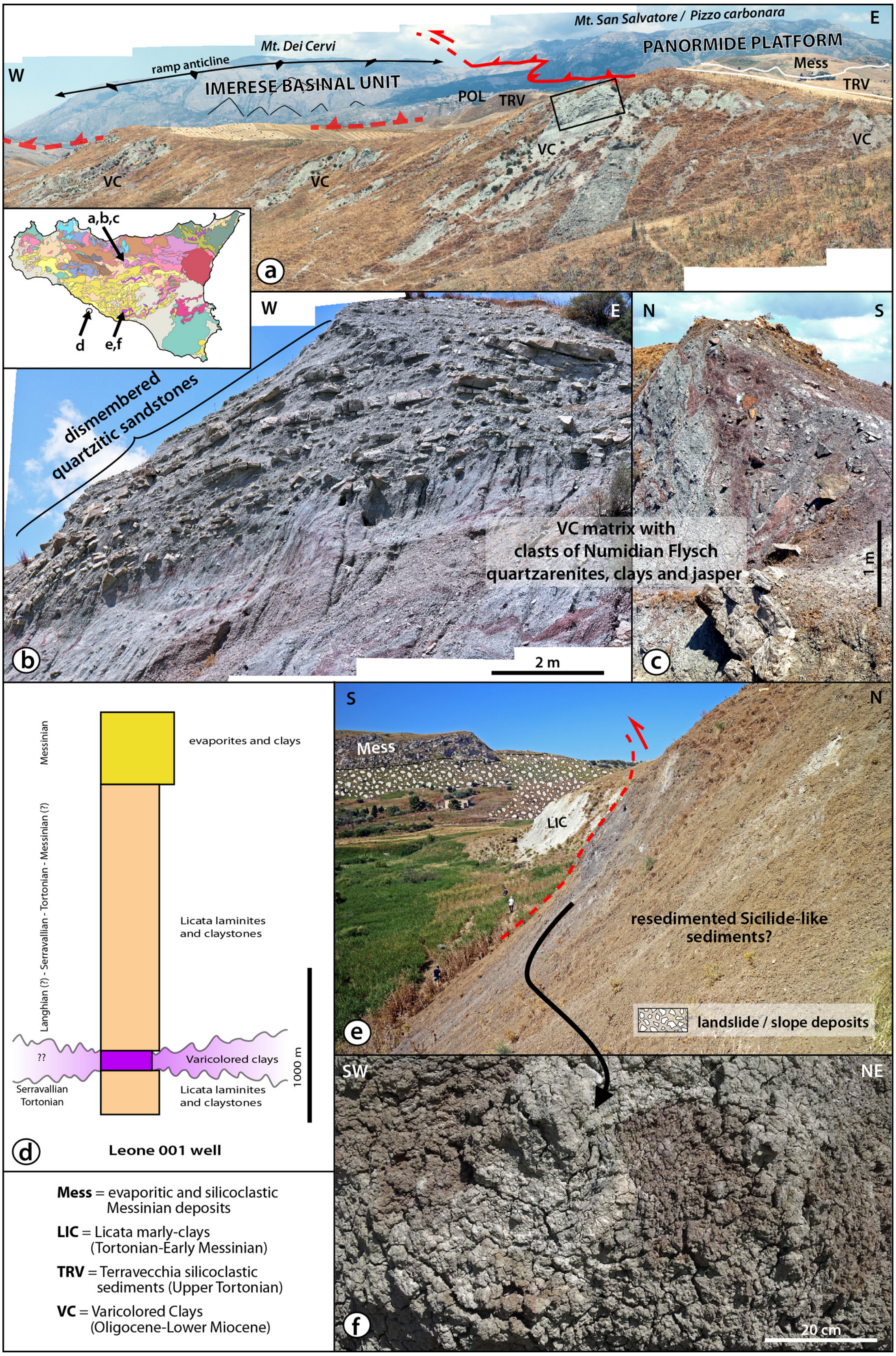
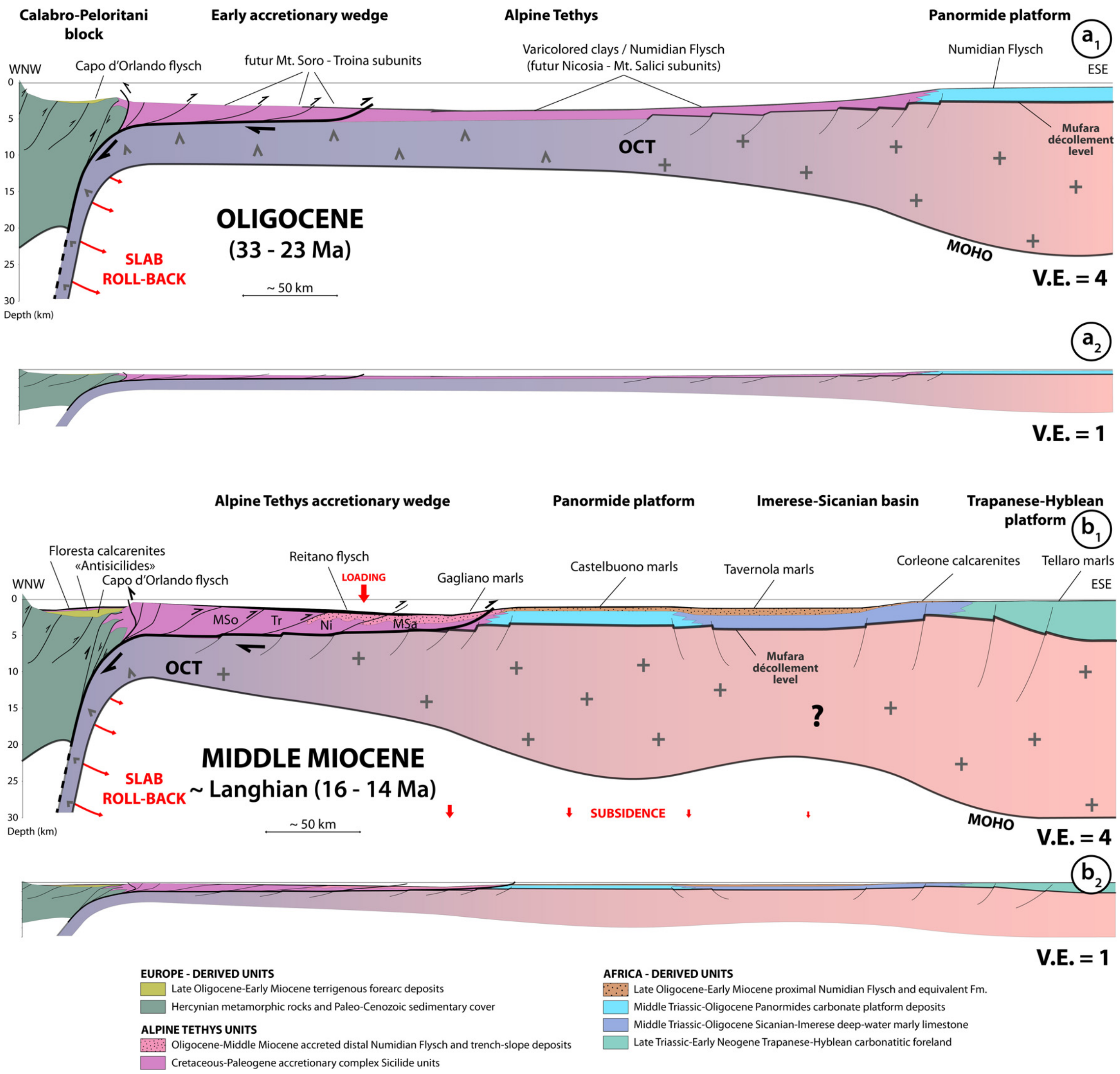
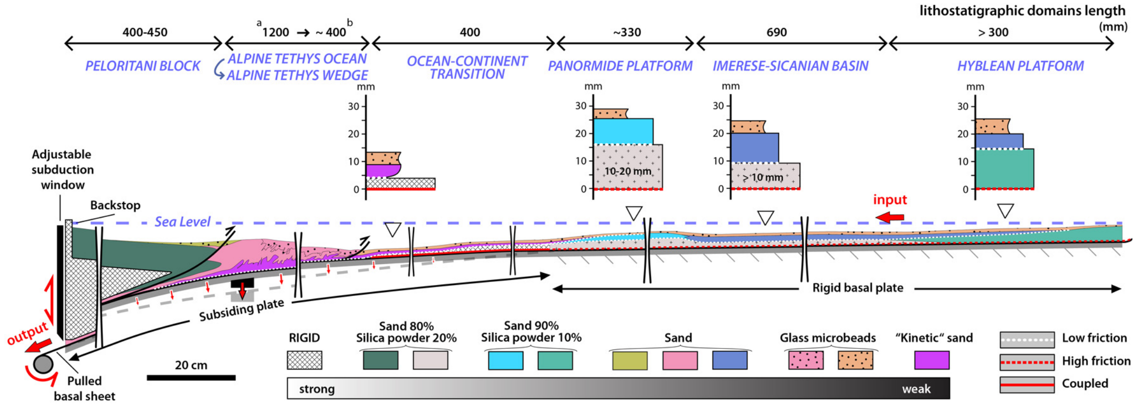

W
E
Mt. San Salvatore / Pizzo carbonara
PANORMIDE PLATFORM
Mt. Dei Cervi
ramp anticline
IMERESE BASINAL UNIT
Mess
TRV
POL
TRV
VC
VC
VC
VC
a,b,c
d
e,f
a
W
E
dismembered quartzitic sandstones
VC matrix with clasts of Numidian Flysch quartzarenites, clays and jasper
2 m
b
N
S
1 m
c
Messinian
Langhian (?) - Serravallian - Tortonian - Messinian (?)
evaporites and clays
Licata laminites and claystones
??
Varicolored clays
Serravallian Tortonian
Licata laminites and claystones
1000 m
d
Leone 001 well
S
N
Mess
LIC
resedimented Sicilide-like sediments?
landslide / slope deposits
e
SW
NE
20 cm
f
Mess = evaporitic and silicoclastic Messinian deposits
LIC = Licata marly-clays (Tortonian-Early Messinian)
TRV = Terravecchia silicoclastic sediments (Upper Tortonian)
VC = Varicolored Clays (Oligocene-Lower Miocene)

Figure 8



Calabro-Peloritani block
Early accretionary wedge
Alpine Tethys
Panormide platform
a1
WNW
Capo d'Orlando flysch
futur Mt. Soro - Troina subunits
Varicolored clays / Numidian Flysch
(futur Nicosia - Mt. Salici subunits)
Numidian Flysch
ESE
OCT
Mufara décollement level
OLIGOCENE
(33 - 23 Ma)
SLAB
ROLL-BACK
~ 50 km
MOHO
V.E. = 4
Depth (km)
a2
V.E. = 1
Alpine Tethys accretionary wedge
Panormide platform
Imerese-Sicanian basin
Trapanese-Hyblean platform
b1
Floresta calcarenites
«Antisicilides»
Capo d'Orlando flysch
Reitano flysch
LOADING
Gagliano marls
Castelbuono marls
Tavernola marls
Corleone calcarenites
Tellaro marls
MSo
Tr
Ni
MSa
OCT
Mufara décollement level
MIDDLE MIOCENE
~ Langhian (16 - 14 Ma)
SLAB
ROLL-BACK
SUBSIDENCE
~ 50 km
MOHO
V.E. = 4
b2
V.E. = 1
EUROPE - DERIVED UNITS
Late Oligocene-Early Miocene terrigenous forearc deposits
Hercynian metamorphic rocks and Paleo-Cenozoic sedimentary cover
ALPINE TETHYS UNITS
Oligocene-Middle Miocene accreted distal Numidian Flysch and trench-slope deposits
Cretaceous-Paleogene accretionary complex Sicilide units
AFRICA - DERIVED UNITS
Late Oligocene-Early Miocene proximal Numidian Flysch and equivalent Fm.
Middle Triassic-Oligocene Panormides carbonate platform deposits
Middle Triassic-Oligocene Sicanian-Imerese deep-water marly limestone
Late Triassic-Early Neogene Trapanese-Hyblean carbonatitic foreland

Figure 9



lithostatigraphic domains length (mm)
400-450
1200 → ~400
400
~330
690
> 300
PELORITANI BLOCK
ALPINE TETHYS OCEAN
ALPINE TETHYS WEDGE
OCEAN-CONTINENT TRANSITION
PANORMIDE PLATFORM
IMERESE-SICANIAN BASIN
HYBLEAN PLATFORM
10-20 mm
> 10 mm
Adjustable subduction window
Backstop
Sea Level
input
output
Subsiding plate
Rigid basal plate
Pulled basal sheet
20 cm
RIGID
Sand 80% Silica powder 20%
Sand 90% Silica powder 10%
Sand
Glass microbeads
"Kinetic" sand
Low friction
High friction
Coupled
strong
weak

Figure 10

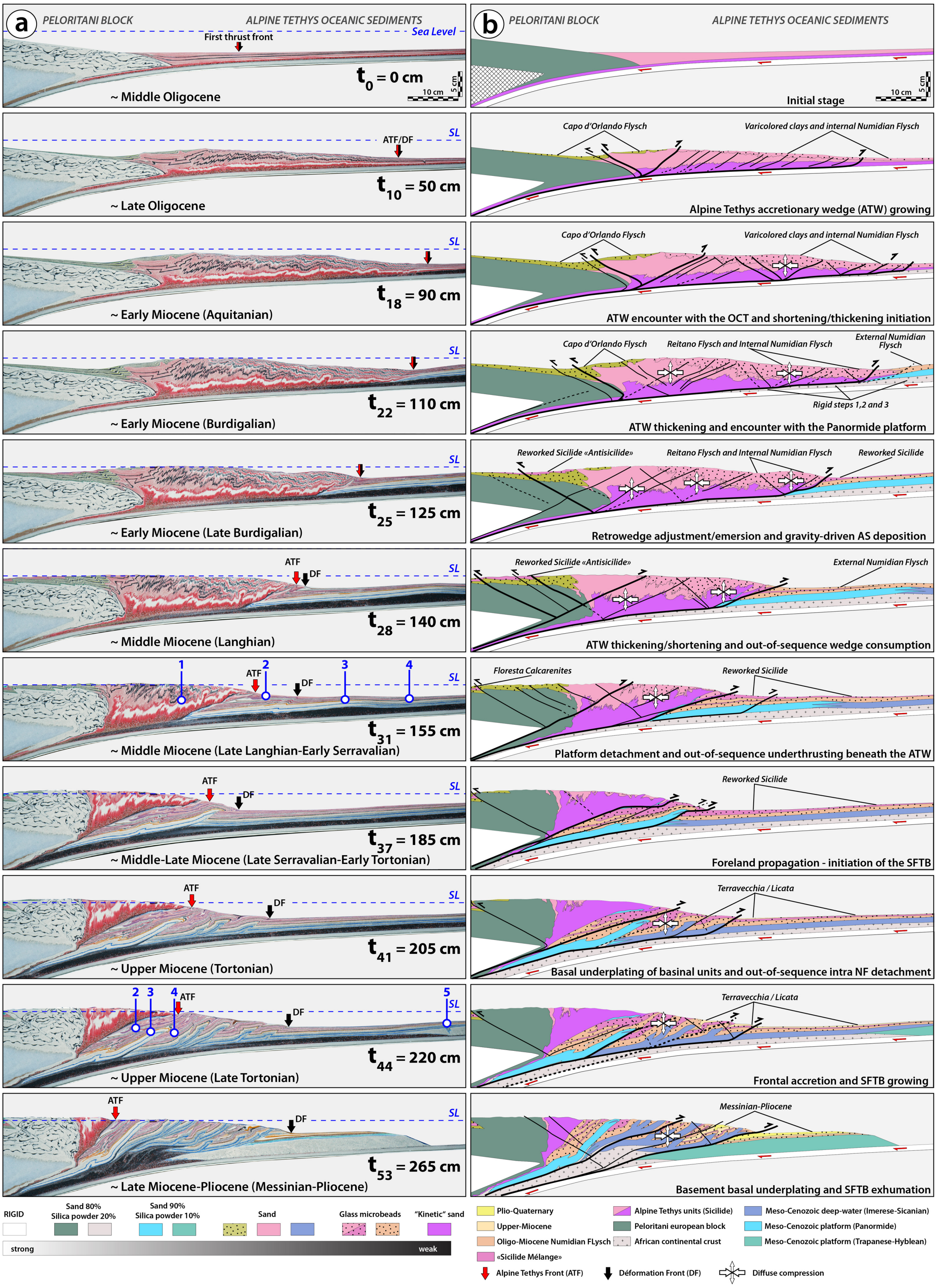

a
PELORITANI BLOCK
ALPINE TETHYS OCEANIC SEDIMENTS
Sea Level
First thrust front
t0 = 0 cm
~ Middle Oligocene
ATF/DF
t10 = 50 cm
~ Late Oligocene
t18 = 90 cm
~ Early Miocene (Aquitanian)
t22 = 110 cm
~ Early Miocene (Burdigalian)
t25 = 125 cm
~ Early Miocene (Late Burdigalian)
t28 = 140 cm
~ Middle Miocene (Langhian)
t31 = 155 cm
~ Middle Miocene (Late Langhian-Early Serravalian)
t37 = 185 cm
~ Middle-Late Miocene (Late Serravalian-Early Tortonian)
t41 = 205 cm
~ Upper Miocene (Tortonian)
t44 = 220 cm
~ Upper Miocene (Late Tortonian)
t53 = 265 cm
~ Late Miocene-Pliocene (Messinian-Pliocene)
b
Initial stage
Capo d'Orlando Flysch
Varicolored clays and internal Numidian Flysch
Alpine Tethys accretionary wedge (ATW) growing
ATW encounter with the OCT and shortening/thickening initiation
Reitano Flysch and Internal Numidian Flysch
External Numidian Flysch
Rigid steps 1,2 and 3
ATW thickening and encounter with the Panormide platform
Reworked Sicilide «Antisicilide»
Reworked Sicilide
Retrowedge adjustment/emersion and gravity-driven AS deposition
ATW thickening/shortening and out-of-sequence wedge consumption
Floresta Calcarenites
Platform detachment and out-of-sequence underthrusting beneath the ATW
Foreland propagation - initiation of the SFTB
Terravecchia / Licata
Basal underplating of basinal units and out-of-sequence intra NF detachment
Frontal accretion and SFTB growing
Messinian-Pliocene
Basement basal underplating and SFTB exhumation
RIGID
Sand 80% Silica powder 20%
Sand 90% Silica powder 10%
Sand
Glass microbeads
"Kinetic" sand
strong
weak
Plio-Quaternary
Upper-Miocene
Oligo-Miocene Numidian FLysch
«Sicilide Mélange»
Alpine Tethys units (Sicilide)
Peloritani european block
African continental crust
Meso-Cenozoic deep-water (Imerese-Sicanian)
Meso-Cenozoic platform (Panormide)
Meso-Cenozoic platform (Trapanese-Hyblean)
Alpine Tethys Front (ATF)
Déformation Front (DF)
Diffuse compression

Figure 11

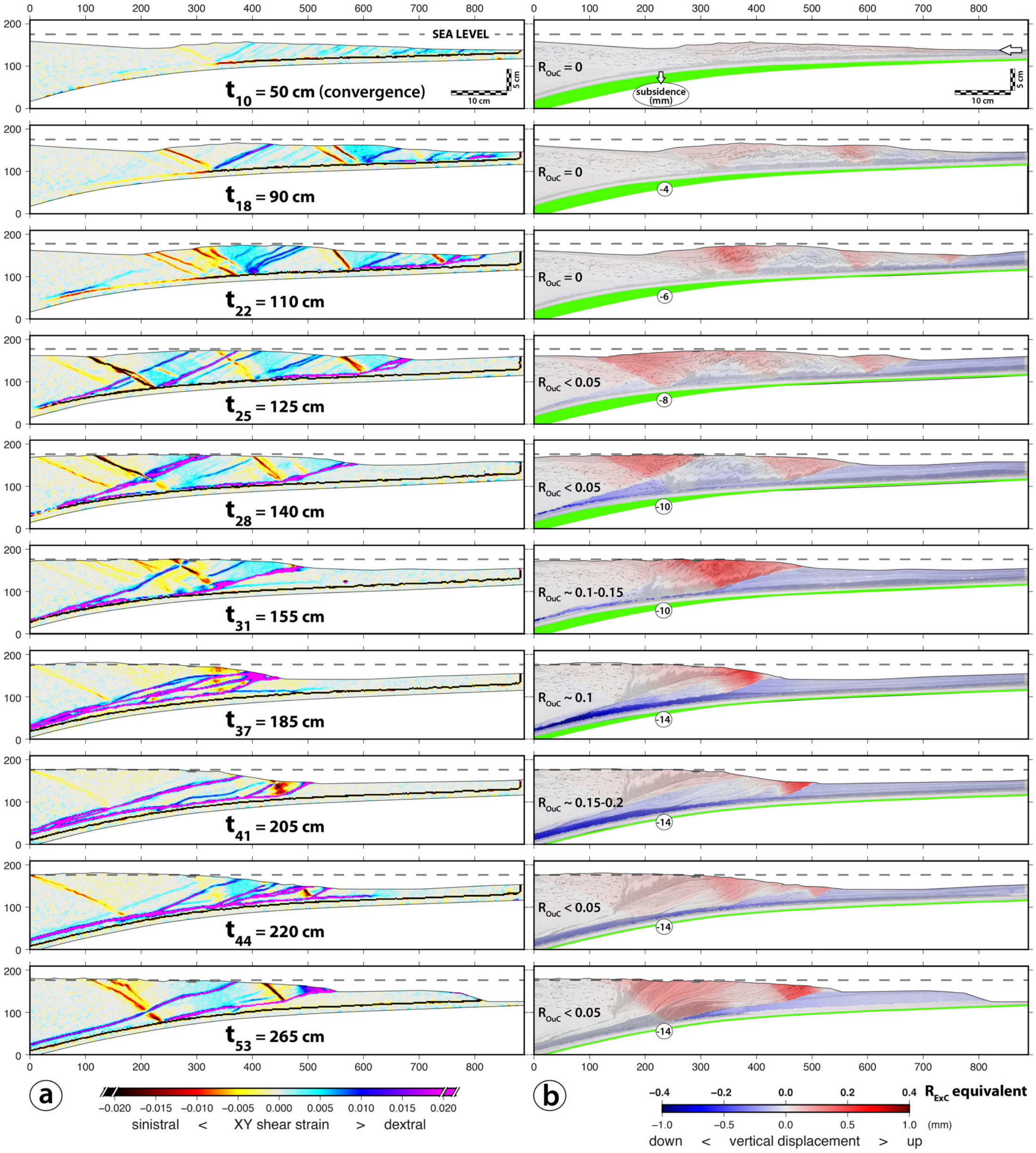

SEA LEVEL
t10 = 50 cm (convergence)
t18 = 90 cm
t22 = 110 cm
t25 = 125 cm
t28 = 140 cm
t31 = 155 cm
t37 = 185 cm
t41 = 205 cm
t44 = 220 cm
t53 = 265 cm
ROuC = 0
ROuC < 0.05
ROuC ~ 0.1-0.15
ROuC ~ 0.1
ROuC ~ 0.15-0.2
subsidence (mm)
10 cm
5 cm
a
b
sinistral < XY shear strain > dextral
REXC equivalent
down < vertical displacement > up
(mm)

Figure 12

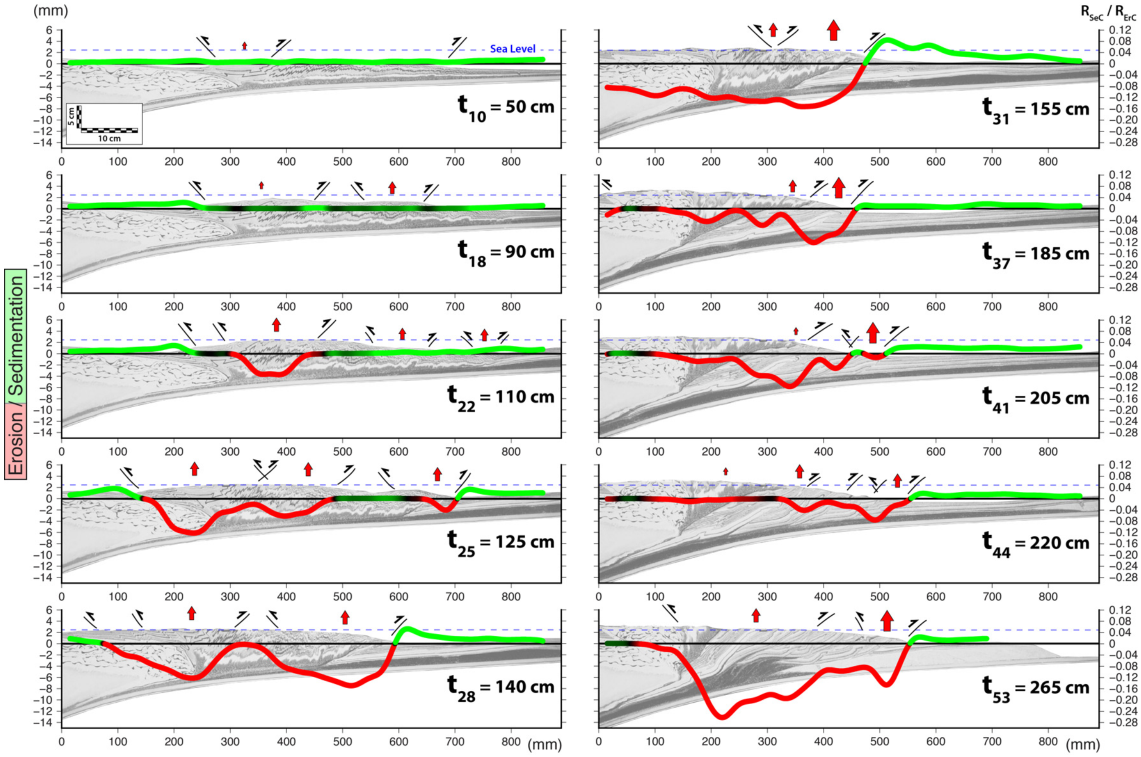

(mm)
Sea Level
t10 = 50 cm
t18 = 90 cm
t22 = 110 cm
t25 = 125 cm
t28 = 140 cm
t31 = 155 cm
t37 = 185 cm
t41 = 205 cm
t44 = 220 cm
t53 = 265 cm
Erosion / Sedimentation
RSeC / RErC
5 cm
10 cm

Figure 13

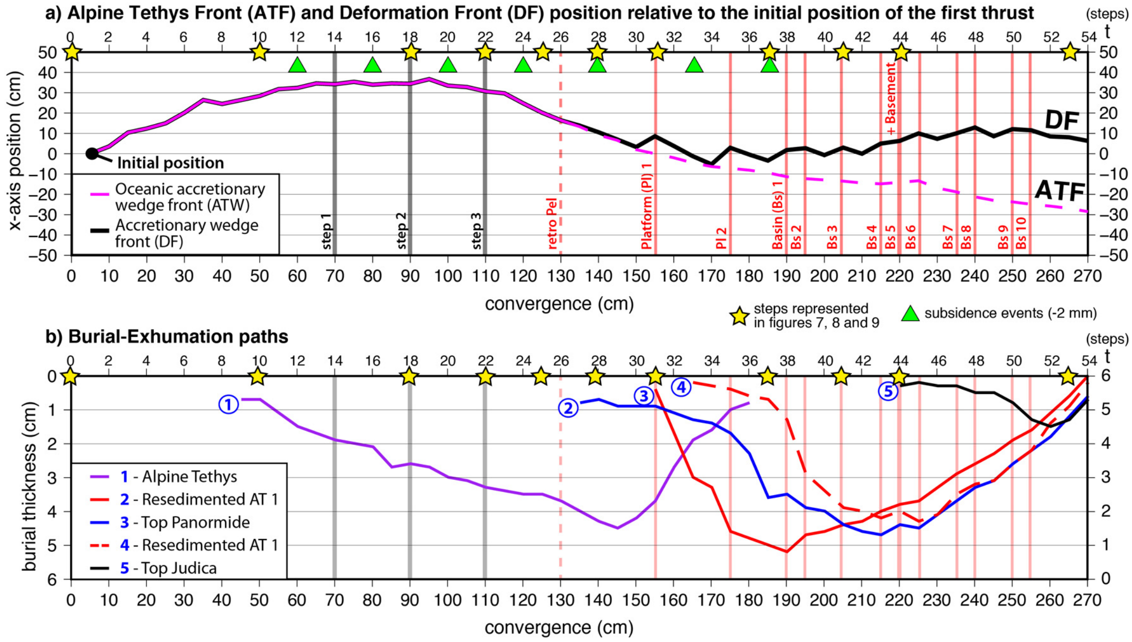
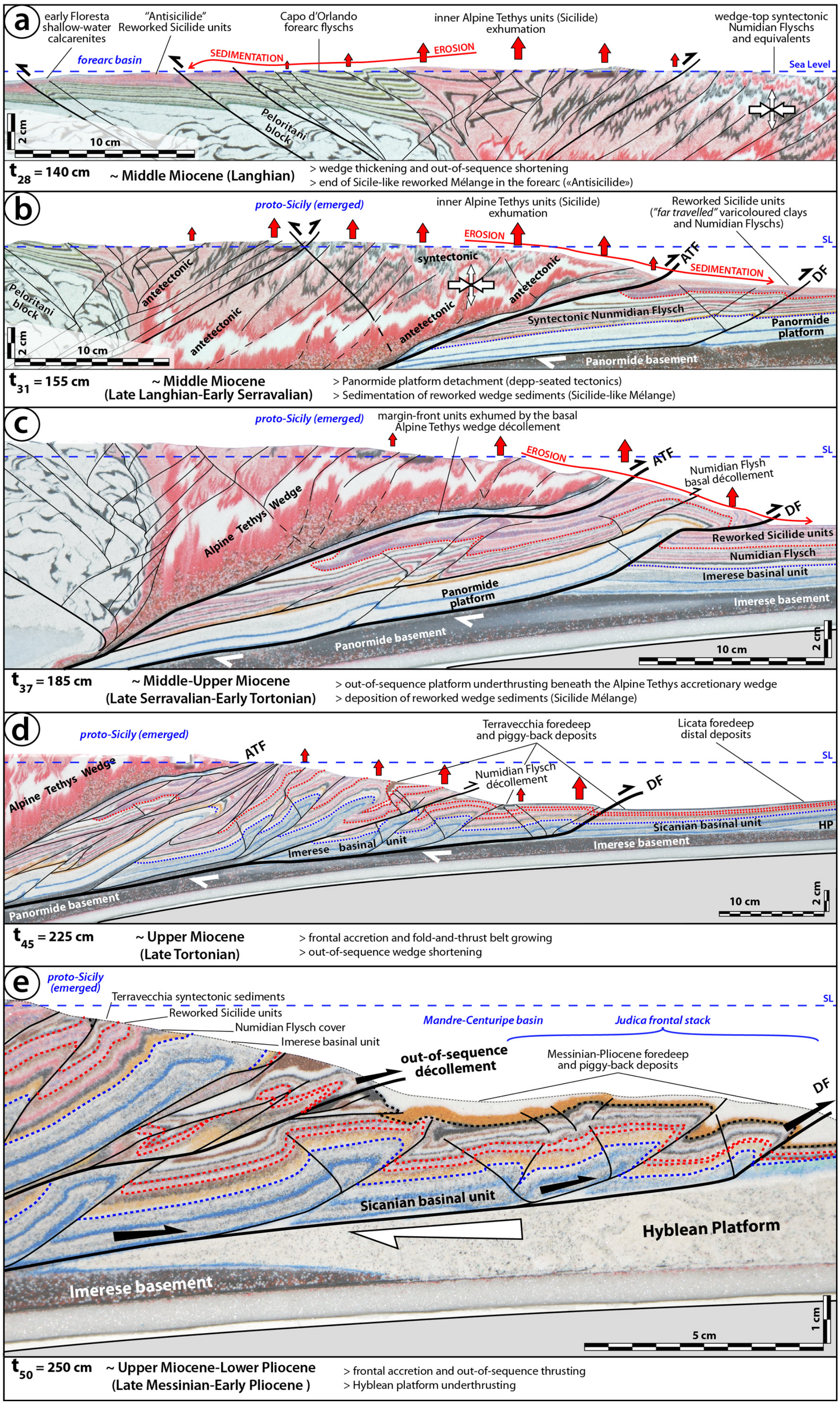
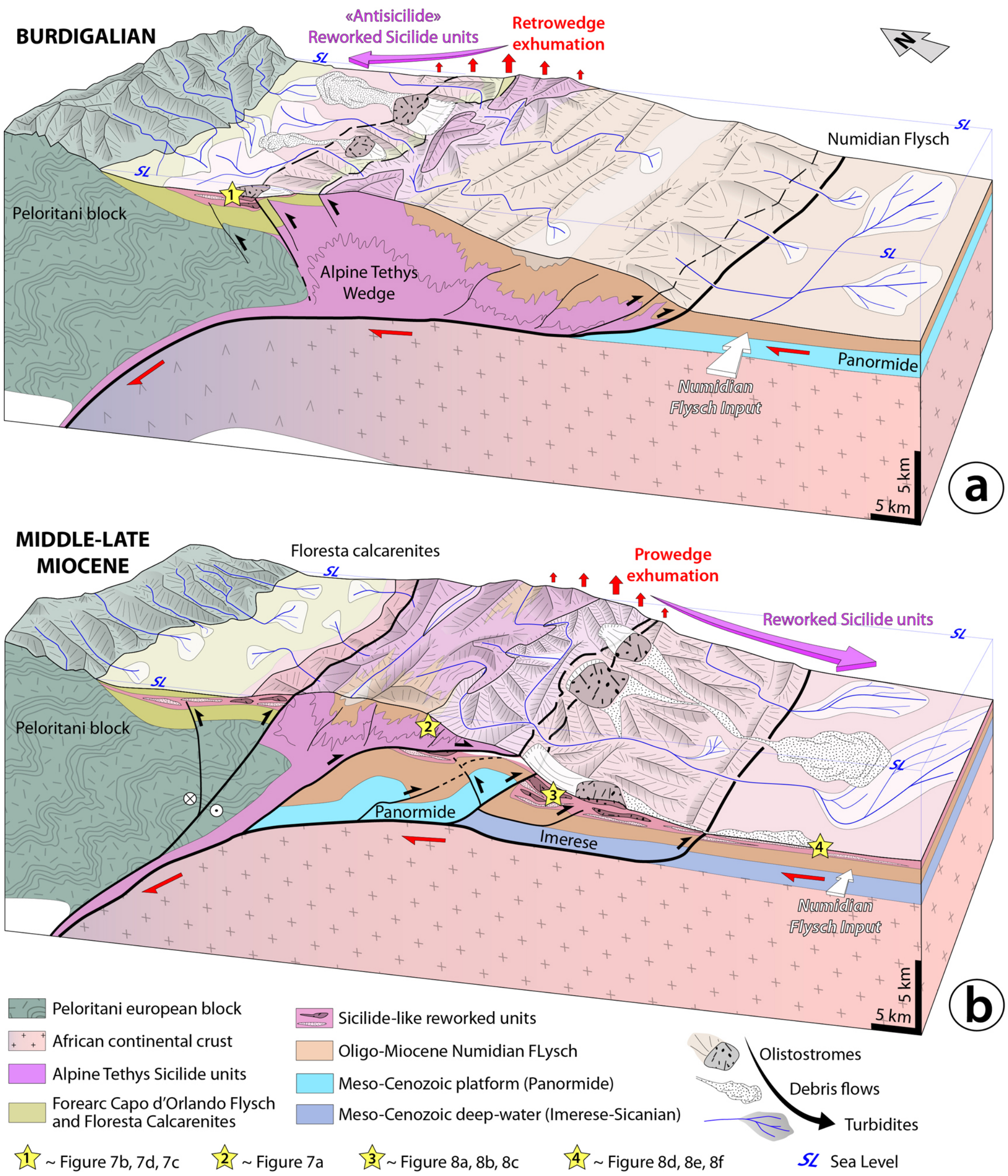

a) Alpine Tethys Front (ATF) and Deformation Front (DF) position relative to the initial position of the first thrust
(steps)
x-axis position (cm)
Initial position
Oceanic accretionary wedge front (ATW)
Accretionary wedge front (DF)
step 1
step 2
step 3
retro Pel
Platform (Pl) 1
Pl 2
Basin (Bs) 1
Bs 2
Bs 3
Bs 4
Bs 5
Bs 6
Bs 7
Bs 8
Bs 9
Bs 10
+ Basement
DF
ATF
convergence (cm)
steps represented in figures 7, 8 and 9
subsidence events (-2 mm)
b) Burial-Exhumation paths
(steps)
burial thickness (cm)
1 - Alpine Tethys
2 - Resedimented AT 1
3 - Top Panormide
4 - Resedimented AT 1
5 - Top Judica
convergence (cm)

Figure 14



a
early Floresta shallow-water calcarenites
"Antisicilide" Reworked Sicilide units
Capo d'Orlando forearc flyschs
inner Alpine Tethys units (Sicilide) exhumation
wedge-top syntectonic Numidian Flyschs and equivalents
forearc basin
SEDIMENTATION
EROSION
Sea Level
Peloritani block
2 cm
10 cm
t_{28} = 140 cm
~ Middle Miocene (Langhian)
> wedge thickening and out-of-sequence shortening
> end of Sicile-like reworked Mélange in the forearc («Antisicilide»)
b
proto-Sicily (emerged)
inner Alpine Tethys units (Sicilide) exhumation
Reworked Sicilide units ("far travelled" varicoloured clays and Numidian Flyschs)
EROSION
SL
ATF
SEDIMENTATION
DF
Peloritani block
antetectonic
syntectonic
Syntectonic Nunmidian Flysch
Panormide platform
Panormide basement
2 cm
10 cm
t_{31} = 155 cm
~ Middle Miocene (Late Langhian-Early Serravalian)
> Panormide platform detachment (depp-seated tectonics)
> Sedimentation of reworked wedge sediments (Sicilide-like Mélange)
c
proto-Sicily (emerged)
margin-front units exhumed by the basal Alpine Tethys wedge décollement
EROSION
ATF
SL
Numidian Flysh basal décollement
DF
Alpine Tethys Wedge
Reworked Sicilide units
Numidian Flysch
Imerese basinal unit
Imerese basement
Panormide platform
Panormide basement
10 cm
2 cm
t_{37} = 185 cm
~ Middle-Upper Miocene (Late Serravalian-Early Tortonian)
> out-of-sequence platform underthrusting beneath the Alpine Tethys accretionary wedge
> deposition of reworked wedge sediments (Sicilide Mélange)
d
proto-Sicily (emerged)
ATF
Terravecchia foredeep and piggy-back deposits
Licata foredeep distal deposits
SL
Alpine Tethys Wedge
Numidian Flysch décollement
DF
Sicanian basinal unit
HP
Imerese basinal unit
Imerese basement
Panormide basement
10 cm
2 cm
t_{45} = 225 cm
~ Upper Miocene (Late Tortonian)
> frontal accretion and fold-and-thrust belt growing
> out-of-sequence wedge shortening
e
proto-Sicily (emerged)
Terravecchia syntectonic sediments
Reworked Sicilide units
Numidian Flysch cover
Imerese basinal unit
SL
Mandre-Centuripe basin
Judica frontal stack
out-of-sequence décollement
Messinian-Pliocene foredeep and piggy-back deposits
DF
Sicanian basinal unit
Hyblean Platform
Imerese basement
1 cm
5 cm
t_{50} = 250 cm
~ Upper Miocene-Lower Pliocene (Late Messinian-Early Pliocene)
> frontal accretion and out-of-sequence thrusting
> Hyblean platform underthrusting

Figure 15



BURDIGALIAN
«Antisicilide»
Reworked Sicilide units
Retrowedge
exhumation
SL
Numidian Flysch
Peloritani block
Alpine Tethys
Wedge
Panormide
Numidian
Flysch Input
5 km
5 km
a
MIDDLE-LATE
MIOCENE
Floresta calcarenites
Prowedge
exhumation
Reworked Sicilide units
Peloritani block
Panormide
Imerese
Numidian
Flysch Input
b
Peloritani european block
African continental crust
Alpine Tethys Sicilide units
Forearc Capo d'Orlando Flysch
and Floresta Calcarenites
Sicilide-like reworked units
Oligo-Miocene Numidian FLysch
Meso-Cenozoic platform (Panormide)
Meso-Cenozoic deep-water (Imerese-Sicanian)
Olistostromes
Debris flows
Turbidites
~ Figure 7b, 7d, 7c
~ Figure 7a
~ Figure 8a, 8b, 8c
~ Figure 8d, 8e, 8f
Sea Level

Figure 16

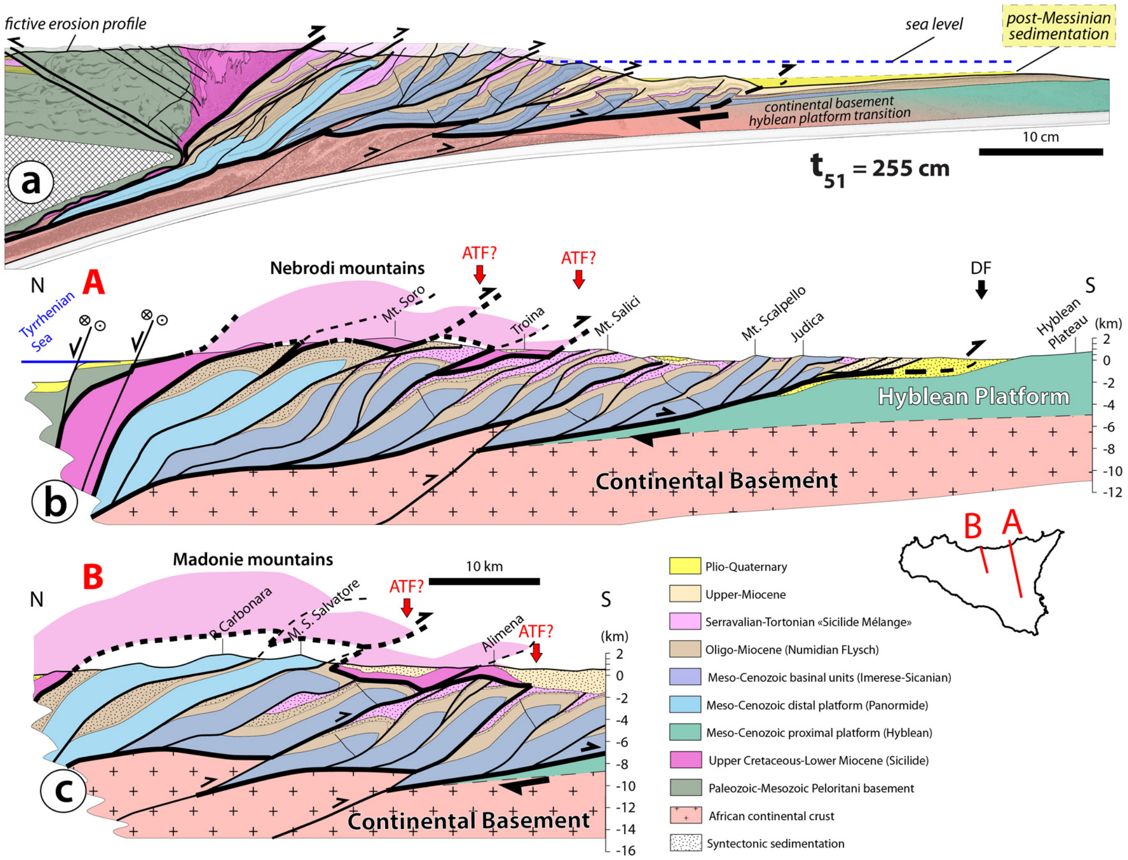

fictive erosion profile
sea level
post-Messinian sedimentation
continental basement hyblean platform transition
10 cm
t51 = 255 cm
a
N
A
Nebrodi mountains
ATF?
ATF?
DF
S
Tyrrhenian Sea
Mt. Soro
Troina
Mt. Salici
Mt. Scalpello
Judica
Hyblean Plateau
(km)
Hyblean Platform
Continental Basement
b
B
Madonie mountains
10 km
N
S
P. Carbonara
M. S. Salvatore
ATF?
Alimena
ATF?
(km)
Continental Basement
c
Plio-Quaternary
Upper-Miocene
Serravalian-Tortonian «Sicilide Mélange»
Oligo-Miocene (Numidian FLysch)
Meso-Cenozoic basinal units (Imerese-Sicanian)
Meso-Cenozoic distal platform (Panormide)
Meso-Cenozoic proximal platform (Hyblean)
Upper Cretaceous-Lower Miocene (Sicilide)
Paleozoic-Mesozoic Peloritani basement
African continental crust
Syntectonic sedimentation

Figure 17